15 Definitive Skeletal Reconstruction: Conversion to the Ilizarov Method

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15.1 Introduction

An acceptable emergency fracture reduction fixation using a unilateral tubular external fixation frame often can be continued until bone healing is completed. However, unilateral external fixation, as a definitive method of skeletal stabilization in patients suffering from high-energy injuries, has been associated with a high rate of nonunion [10, 20, 37]. Therefore, in most cases, it is necessary to achieve secondary optimal fracture reduction and control over the fracture. This will require a transition to other methods of definitive fracture fixation best performed after the final coverage of the wounds has been completed.

Conversion to internal fixation is widely used in low-energy trauma and also in patients suffering from high-energy trauma with ample soft tissue coverage of the fracture zone and the bone fragments (see chapter 14). In severely injured patients who have suffered extensive tissue damage and loss in the fracture zone, conversion to internal fixation methods is prone to serious complications.

The introduction of a surgical fixation implant causes additional trauma to the soft tissues, further reducing the vascularity of the fracture site. Combined with the presence of a large metallic foreign body, compromised soft tissue cover leads to septic complications and nonunion [36]. These circumstances arise in complex combat or terror trauma presenting with extensive deep tissue damage and loss, and multiple foreign bodies in the fracture zone and surrounding soft tissues. To prevent the development of serious complications, final fracture stabilization with a multidimensional and multifunctional method of definitive circular/hybrid external fixation is recommend [17].

Contrary to internal fixation methods, it is not imperative to wait until final and safe fracture site soft tissue coverage has been achieved when using external fixation frames. Bone reconstructive procedures can be safely carried out as early as the first days after injury. This is an important advantage, because closed fracture reduction becomes more difficult the longer the wait for complete wound healing. This has been discussed in the previous chapter on primary fixation.

Unilateral fixation frames have only a limited ability to reposition bone fragments during the fracture reduction procedure. Hence, frequently, the primary tubular external fixation used for the emergency primary stabilization must be changed to a hybrid or ring system to achieve final reduction, stabilization, and control over the fracture. In order to perform this transition efficiently with minimal additional trauma to the patient, we use the Shanz screws from the primary tubular external fixator which were applied initially and add tension wires and additional Shanz screws (as many as required) for the reduction and stable final fixation of the bone fragments.

The extraordinary potential of the Ilizarov method for tissue neogenesis is a solution for almost any extent of bone damage, including massive bone loss. This method allows the performance of radical bone end debridement in the knowledge that future bone length restoration will be possible. Taking into consideration

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the availability of many publications dealing with the Ilizarov method and its application in various orthopedic and trauma conditions, we limit ourselves here to describing the principles that govern the treatment of severe complex fractures of the limbs. A period of specialist training and experience in treating these patients is essential [34].

In the case of severe periarticular fractures, attention must be paid not only to reduction and stable fixation of the bone fragments, but also to releasing the primarily bridged joints as soon as possible, in order to preserve their range of movement. Additional imaging, before the final reconstructive procedure, is mandatory for the diagnosis of missed fractures, foreign bodies, or a distant extension of the fracture. Meticulous preoperative planning of the surgical procedure and the appropriate optimal fixation frame configuration give the best chance for success.

15.2 Conversion from the Unilateral Tubular Fixator to Ilizarov Circular Frame

One of the principal advantages of the circular Ilizarov frame is the ongoing ability to actively influence the position of the bone fragments during the entire period of external fixation [29]. This allows guided, closed, gradual, atraumatic, and pain-free final alignment of the bone fragments, without the need to attain immediate definitive reduction surgically (a onetime potentially traumatizing procedure involving soft tissue tension around the bone fragments causing vascular disturbance in the bone fragments, especially undesirable in high-energy injuries).

Five to seven days following trauma (or when the general and local soft tissue conditions permit), the unilateral tubular external fixator can be exchanged for a circular or hybrid fixation frame that enables the closed final fracture reduction and early functional mobilization (including full weight-bearing) [16] (Fig. 15.1). To optimize the sterility of the operative field, the primarily placed unilateral external fixation frame is removed before the ultimate preoperative cleaning of the injured limb segment. At this time, the tubes of the unilateral frame are removed and the stability of fixation of each of the Shanz screws is examined. It is desirable to preserve and use Shanz screws of the primary fixation frame without signs of local pin-tract infection, having good fixation to the bone and situated in the "correct localization," that is, Shanz screws that do not transfix muscles and tendons and joint capsule. Unstable Shanz screws, screws with signs of local infection, and screws located over tendon-muscle units resulting in the restriction of joint motions must be removed.

15.3 Preserving Bone Alignment During the Conversion Procedure

It is desirable to preserve good bone fragment reduction achieved by the primary operative skeletal stabilization during the conversion procedure from the unilateral tubular external fixation frame to the circular Ilizarov or hybrid external fixation device. When there is a good primary fracture reduction, redundant parts of the primary tubular external fixator should be removed only after the final hybrid or circular frame provides bone fragment stabilization. In order to perform this transition efficiently and with minimal additional tissue traumatization, we recommend, whenever possible, the inclusion of the primarily inserted half-pins of the cantilever tubular external fixator to the final circular frame [17] (Fig. 15.2).

To attach the Shanz screws to the circular Ilizarov frame without loss of fracture fixation, we recommend the following steps. To make room for the circular frame, the tube more distant from the limb of the double unilateral tubular frame must be moved even further toward the outer ends of the Shanz screws and then strongly reattached. Thereafter, the tube placed nearer the injured limb segment can be removed. Thus, an adequate space is provided for mounting a circular external fixation frame around the still fixed segment, preserving the previously achieved alignment. Then, the Shanz screws of the primary tubular external fixator should be firmly attached to the circular frame by affixing them to the corresponding rings.

Under these special circumstances, to maintain the sterility of the operative field during the conversion procedure, the inner hollow of the tubes of the primary external fixator are flushed copiously and frequently, using a syringe charged with an antiseptic solution. Similarly, at each stage, the Schanz screw surface underneath released clamps is rinsed with an antiseptic solution (Fig. 15.3).

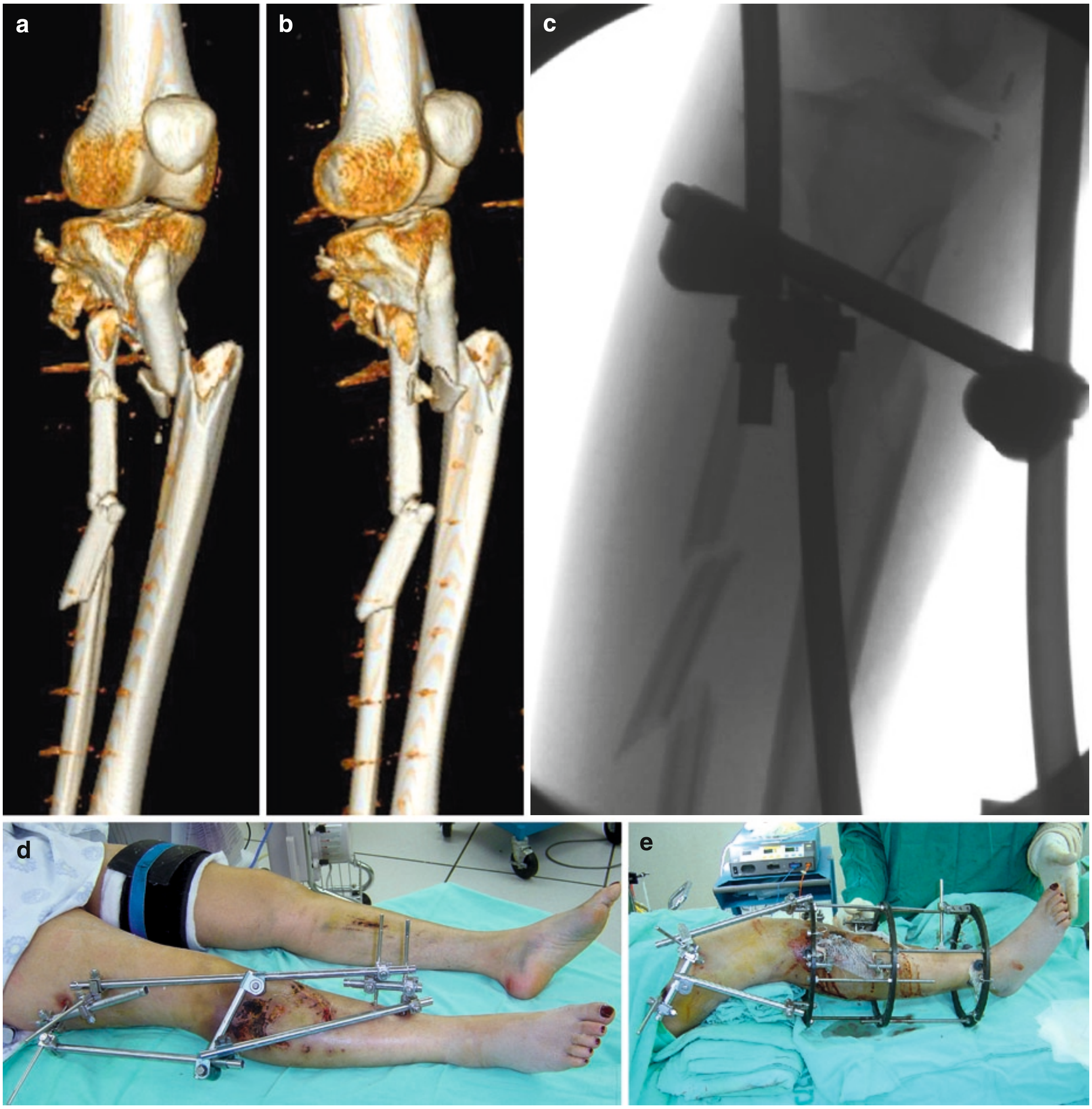


Fig. 15.1 A 30-year-old female who sustained multiple high-energy trauma with open comminuted right leg fractures. Primary skeletal stabilization of the right lower limb was achieved using bridging unilateral external fixation frames in the context of "damage control" surgery. (**a**, **b**) CT reconstruction pictures at admission demonstrate comminuted displaced fractures of proximal tibial and fibular bones. (**c**) Radiological picture after axial realignment and primary external fixation for emergency stabilization. (**d**) Clinical appearance of bridging external fixation of right lower limb. Note signs of soft tissue damage around the knee joint and proximal leg. (**e**) After 5 days, conversion to hybrid/Ilizarov external fixation frame with closed reduction of tibial fractures was performed. Temporary knee bridging was continued for additional 4 weeks due to extensive soft tissue damage around the knee joint. Clinical picture after conversion demonstrates the inclusion into the new fixation frame of half-pins from the primary tubular frame. (**f**, **g**) Fixation in the Ilizarov external fixation frame was continued after freeing the knee (removal of the bridging); active knee mobilization and full weight-bearing on the right leg was allowed. Radiological pictures after 7 months of external fixation demonstrate the bone-healing process and good alignment. (**h**) Radiological appearance at a 2-year follow-up demonstrates bone healing of the right tibial fracture in good alignment

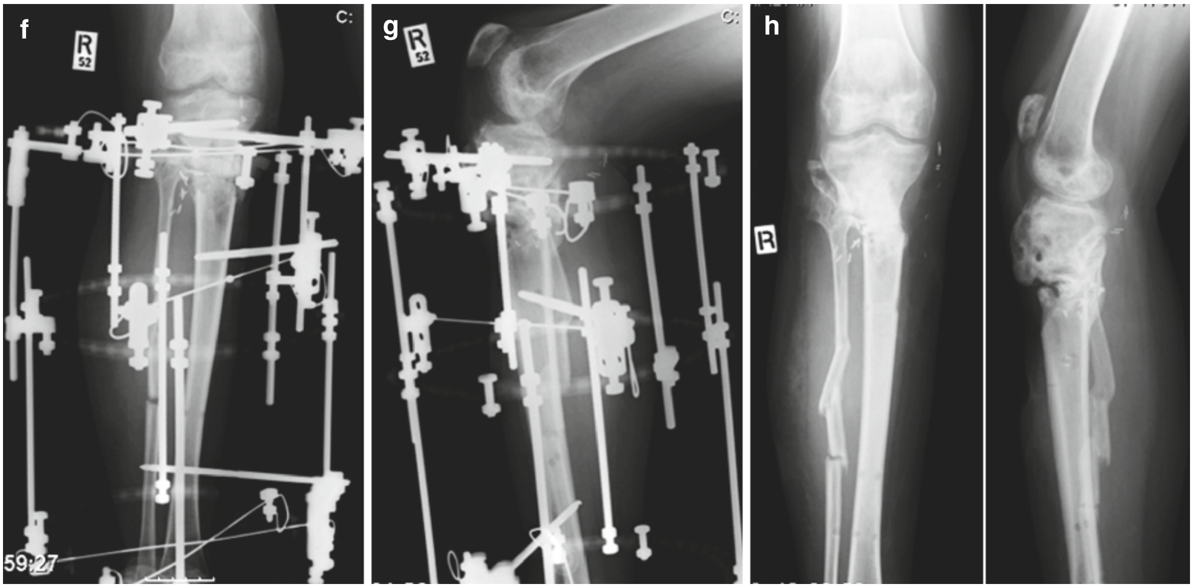


Fig. 15.1 (continued)

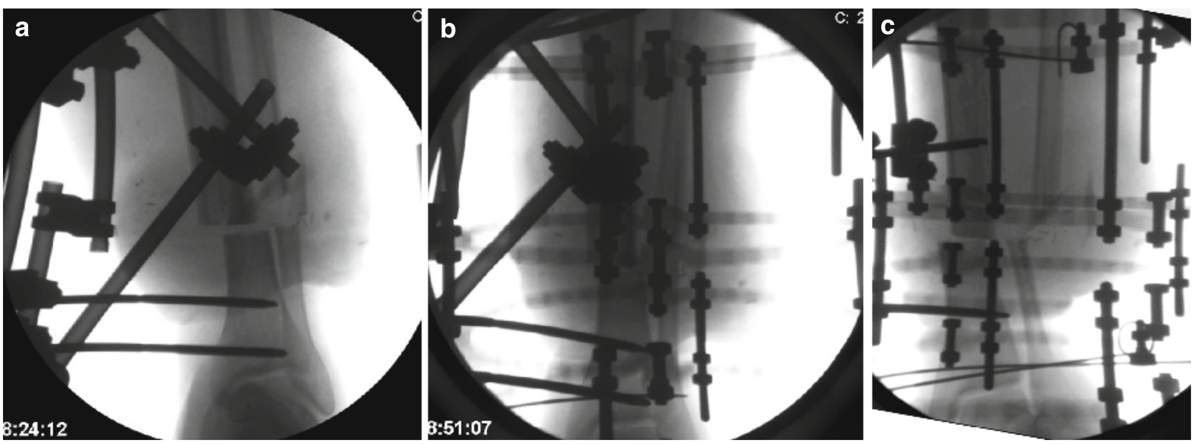


Fig. 15.2 Radiological appearance of conversion stages from tubular to circular external fixation frame. (**a**) Radiological pictures demonstrate external fixation of the right tibial fracture using tubular fixation frame. (**b**) Intraoperative radiogram demonstrates conversion to an Ilizarov circular frame *by the temporary retention of the previous stabilization* in the primarily placed tubular frame. (**c**) External tubular frame was removed only after stable fixation of the tibial bone in the circular frame was performed

It is undesirable to reuse the contaminated removed elements of a primary fixation frame without first carefully resterilizing them. Optimally, only presterilized fixation elements should be used!

To the most proximal ring of the Ilizarov frame, we attach the supporting post-masculine or post-feminine end. The proximal half-pin is fastened to the supporting post-masculine end or post-feminine end using an encircling buckle with nuts. A similar fixation procedure is arranged to the distal ring of the circular device. Additional thin wires and half-pins are introduced to the main bone fragments and only now, after ensuring the stability of the fracture fixation, the remaining tube of the primary unilateral fixation frame is removed. Thus, the hazard of secondary displacement of the bone fragments with loss of alignment and additional

Fig. 15.3 Cleaning inner hollow of the tubes of the unilateral external fixator using antiseptic solution

traumatization to the soft tissues can be avoided, the operative procedure can be shortened, and the exposure to intraoperative irradiation of the patient and operating staff is diminished. Finally, more tension wires and additional Shanz screws to correct inadequate positioning of bone fragments and to provide final stabile fixation are added. The number of rings, transosseous wires, and Shanz screws vary according to fracture patterns (Fig. 15.4).

Moreover, part of this procedure (mounting of the circular external frame on the base of the available Shanz screws of the primary tubular external fixator) does not need anesthesia and can be performed directly in the hospital ward, saving operating room time, as only additional tension wires and Shanz screws need to be inserted later under anesthesia (useful in the mass casualty situation when operating room and anesthesia time are at a premium).

15.4 Ilizarov Frame Assembly Technique for Fracture Reposition and Fixation

15.4.1 General Principles

Different methods of Ilizarov frame assembly exist:

(a) Preliminary mounting of the fixation frame before surgery
(b) Mounting the circular frame around the fixed limbs' segment during surgery
(c) Separate mounting of the proximal and distal fixation blocks of the frame above corresponding proximal and distal main bone fragments that are set in a position of realignment and then firmly connected together by the frame

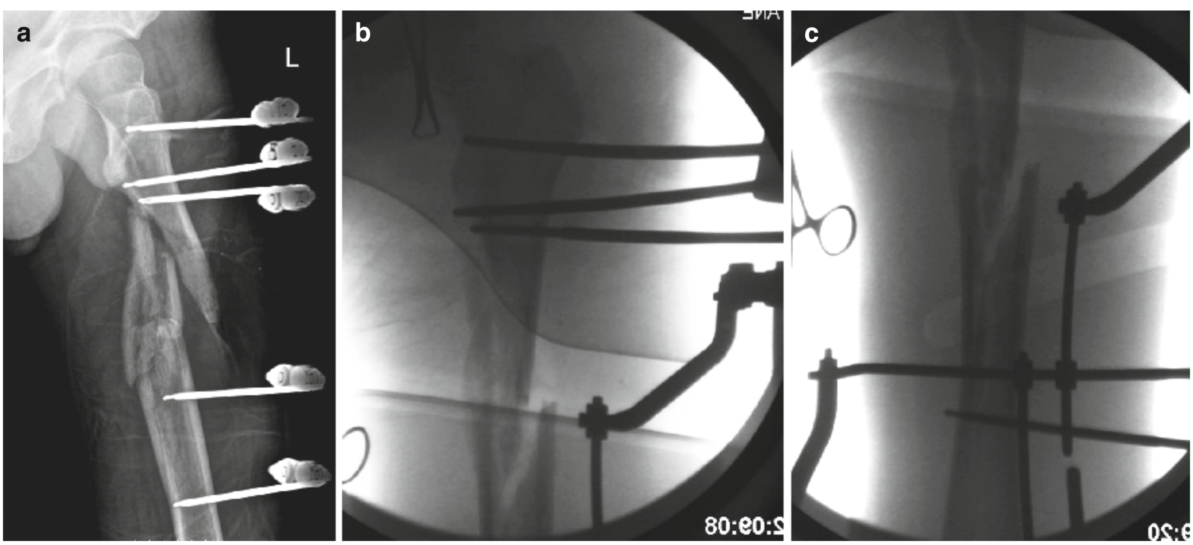


Fig. 15.4 (**a**, **b**) Radiological pictures demonstrate conversion from tubular to circular external fixation of the comminuted femoral fracture in a patient who suffered from GSW to left lower limb. (**a**) Primary external fixation using unilateral tubular external fixation frame. (**b**, **c**) Conversion to Ilizarov external fixation frame using Shanz screws from the cantilevered primary tubular frame and closed reduction of the fracture in the circular frame

When the mounting of an Ilizarov/hybrid frame is planned, we recommend the preliminary assembly of the external fixation circular frame before surgery. Preliminary frame assembly reduces operative time. Standard ring constructions that have been assembled in advance should be kept sterile according to the common practice of sterilization and storage for surgical instruments [2]. To facilitate storage and sterilization, the frame can be divided into two half-ring-based assembly groups.

The inner diameter of assembled rings must be at least 4–5 cm larger than the maximum diameter of the appropriative operated limb segment. After fitting the circular frame on the injured segment of the limb and correcting the rings' position according to the location of the fixed bone fragments, the frame is stabilized. If this necessary stabilization of the frame itself is not executed at this early stage of the operation, one or two nuts found to be loose later during the procedure may result in a loss of the entire system's stability, and also in the loss of the frame's reduction effectiveness. Moreover, if early stabilization of the frame is neglected, the forces acting during the guided transfer of displaced bone fragments will result in unexpected deformities of the fixation frame itself. This mistake can cause technical difficulties and wastes considerable effort and time, necessitating a repetition of earlier stages of the operative procedure.

For convenience of the procedure and the simplification of aperture choice on the rings for fixing thin wires and Shanz screws, each pair of rings of a pre-adjustment frame is first connected to each other by only two threaded rods (not yet by four rods as used in the finished frame). However, such a device is insufficiently stable for fracture reduction. The stress created during fracture reduction can lead to a deformation of the incomplete fixation device. Therefore, after wire and Schanz screw fixation to the corresponding rings and before performing the fracture reposition, it is necessary to extend the mechanical stability of the frame by increasing the number of threaded rods up to four (the recommended number of the interring rods), and only then to carry out the reduction.

Just as in unilateral frames, if the location of the proximal and distal levels of fixation (rings) is distanced from the site of the fracture as much as possible and the intermediate rings are close to the fracture site (long lever arm fixation of main distal and proximal bone fragments), rigidity of stabilization in the circular frame will be enhanced. A short frame may be more comfortable for the patients in their daily activities but, due to its lesser stability, may create significant problems during the course of the treatment.

High-energy injuries are associated with severe post-traumatic swelling of the injured limb. This, and the necessity to preserve a sufficient space for the approach to soft tissue wounds, dictate the need to apply larger-diameter rings than is usually recommended in the assembling of the circular frame in standard situations (recommended distance between the skin of the fixed limb segment and the frame is about 2–3 cm in the standard situation), according to each particular circumstance (Figs. 15.5 and 15.6).

Increasing the ring diameter results in a reduction in bone fragment fixation stability. The longer the wire lever length and the larger the ring diameter, the less the mechanical stability of the fracture fragment fixation. To eliminate this undesirable effect, we recommend, when using large-diameter frames, the insertion of one or two more thin wires or half-pins into each of the main bone fragments, and also the installation of additional threaded rods between the rings. Increased stability of the fracture fixation can also be achieved by the use of olive wires in the fixation construction.

The number of rings in the external frame is also directly proportional to the degree of mechanical system stability and, correspondingly, to the reliability of fracture fixation. The standard Ilizarov fixation frame usually contains four rings, two per fixed main bone segment. Especially when using large-diameter rings,

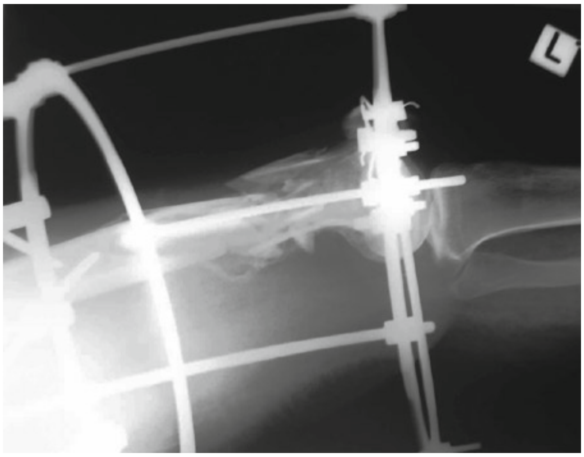


Fig. 15.5 Radiological picture demonstrates high-energy distal femoral fracture stabilized using an Ilizarov frame with big-diameter rings

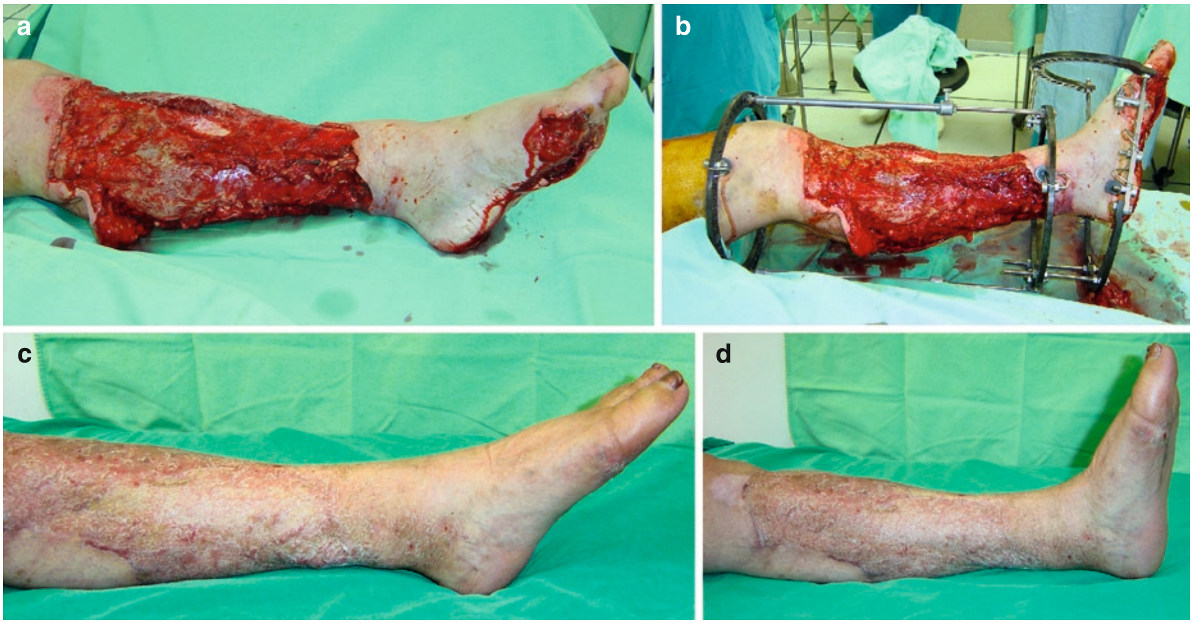


Fig. 15.6 Big-rings circular fixation frame used for bone stabilization and soft tissue protection in the treatment of open tibial and foot fractures with circular skin degloving. (**a**) Clinical picture demonstrates extensive left lower limb degloving injury. (**b**) External fixation using trans-ankle Ilizarov external fixation. (**c**, **d**) Clinical pictures at a 2-year follow-up demonstrate good ankle ROM

it is very important to remember the need for two-level fixation of each main bone fragment. One or even two additional rings are needed for stable fixation and active influence on isolated intermediate large bone fragments when treating patients suffering from segmental fractures. In the assembly of the external fixation frame, including large-diameter rings, one or two additional threaded connection rods must by placed between the rings. The rods should be oriented perpendicularly to the rings; oblique or bent positioning of the connecting rods will lead to the deformation of the construct when tightening the nuts and must be avoided. The frame stability is inversely proportional to the distance between the rings above and below the fracture and, consequently, additional threaded rods must be included to the fixation frame with relatively large interring distance in the treatment of patients suffering from extensive bone comminuting.

Two thin wires per ring are usually used in the standard configuration of the Ilizarov frame. The greatest stability is obtained with a 90° crossing of the ring wires. In practice, to avoid soft tissue transfixation, the wire-crossing angle is often considerably less and, thus, the stability is decreased, especially when angulation between the wires is less than 45°. Using thin wires with olives can raise the level of mechanical bone stability in the fixation frame. A similar effect can be achieved by using large-diameter Shanz screws; therefore, for fixation of femoral or tibial bones, we usually use 6-mm-diameter half-pins. Internal stability provided by direct contact of main bone fragments can contribute to the general stability provided by the external fixator. In transverse fractures, shearing forces can be controlled by applying simple compression across the fracture site. The victims of high-energy injuries, especially war injuries, usually suffer from comminuted fractures, often with some bone loss. In such situations, in the early stages of the treatment, stability is provided only by the fixation frame itself. Consequently, some additional fixation elements (thin wires, half-pins) must be added to increase the level of stability of each main bone fragment and, correspondingly, of the whole external fixation construct.

It is possible also to avoid unnecessary fixation frame enlargement by the asymmetrical placement of the fixed limb segment into the circular fixation frame, preserving a greater distance between the skin and the inner part of the ring only on the inferior-dependent surface of the limb, since the likelihood of swelling is greatest on the posterior aspect of the thigh, calf, arm, and forearm. However, even when using asymmetric positioning of the injured limb segment in the external fixation frame, it is necessary to ensure symmetrical fixation of the distal bone fragment with regard to the proximal one. Asymmetrical positioning of a limb segment in the frame, especially asymmetrical localization of the bone relative to the center of the frame, diminishes the stability of fixation.

The circular fixation frame can be modified, supplemented, or simplified at any time postoperatively according to the status of the injured limb and the functional needs at each concrete stage of the rehabilitation process.

Wire insertion technique: Using his free hand and holding a pad moistened in alcohol for additional disinfection and cooling of the wire, the surgeon directs the thin wire. After puncturing the skin and soft tissue and impinging onto the bone, and before proceeding with the drilling, it is desirable to thrust and compress the soft tissues by hand onto the bone; this simple maneuver diminishes the tendency of the soft tissue to be caught up and twist around the rotating wire, creating additional skin and soft tissue damage.

The proper wire diameter should be used to ensure sufficient wire strength and to maintain appropriative stiffness of the fixation frame. The 1.8 mm wires are recommended for femoral, tibial, and humeral fractures in adults, while the 1.5 mm wires are recommended for forearm bone fractures and pediatric patients. Identical to the half-pin insertion technique, low-speed drilling with frequent stops is used to insert the thin wire into the bone to avoid heat necrosis of surrounding soft tissues and bone.

The thin wire must be tensioned to 130 kg and then fixed in the ring of the fixation frame. When performing tightening of the wire to the ring, the head of the fixation bolt is held stationary with one wrench while turning the nut with another. If the non-fixed bolt turns during the tightening procedure, the thin wire will bend, resulting in displacing forces acting on the transfixed bone fragment. The wire fixator must be aligned with the corresponding wire (*but never bend the wire to fit the fixator!*), because tensioning of the bent wire may result in the displacement of the bone fragment fixed by this wire. Bending can be avoided and fixation of the deviated thin wire (or half-pin) can be performed by placing washers between this wire and the ring, or using male- or female-posts in cases of marked deflection of the fixation elements. The orientation of the following additional wires is assisted by observing the direction of previously inserted thin wires and half-pins and their relationship to them, reducing radiation exposure for the patient and surgeon by lessening the frequency of fluoroscopic control.

Do not hasten to remove the undesirably oriented wires – they can serve as useful temporary reference points or as a "joystick" tool.

Insertion of the thin wires not only in the plane of the ring, but also in various other oblique planes improves the fracture's fixation stability. Introduction of wires into the bone from various sites on the ring also creates additional mechanical stability (the bone may be significantly weakened by the insertion of wires from different sites but in one single plane of the ring and thereby cause an iatrogenic fracture – this must be carefully avoided). *Generally, the introduction of thin wires into the bone fragments from various sites on the rings is not only possible, but also desirable*. If a pin or wire creates tension of the soft tissues, restricting the motion in the adjoining joints, it must be withdrawn and reinserted. The entire procedure is performed under fluoroscopic imaging control. The final review is by two plain standard anteroposterior and lateral radiographs, and additional radiographic views if needed.

For equal distribution of functional load-bearing forces during the fixation period, the tension on the various thin wires must be similar: if there are different levels of wire distraction, the more tensioned wire takes a greater load, which can result in its breakage and end with a loss of stability in the circular frame and secondary displacement of the bone fragments.

15.4.2 Specific Locations

15.4.2.1 Femur

During surgery to the thigh, the patient is placed in the supine position with a small sandbag elevation under the buttocks or lumbar zone on the side of the injury. This prevents deformation of the thigh muscle, skin, and soft tissue mass caused by the supine position, and avoids transfixation of the soft tissues by thin wires and half-pins in a nonanatomical shifted position. Noncompliance with these simple positioning principles causes excessive tension of the skin and soft tissues around the implanted wires and pins, leading to pain, pin-tract infection, and joint stiffness. On detecting such soft tissue deformities in the final stage of the operation, it is necessary to release skin tension by small incisions in the skin over the corresponding wires and pins. For gross soft tissue deformities and severe skin tension around implanted elements, it is necessary to reinsert the offending wire or Schanz screw to avoid the complications previously enumerated. A circular frame for the stabilization of femoral fractures usually includes two distal rings and one full ring placed more proximally, with an additional most proximally placed half-ring. For treating fractures in the middle or proximal third of the femoral bone, two proximal half-rings are used (a full ring would create great discomfort at the level of the upper one-third of the thigh). A distally placed half-ring or 5/8 ring allows early knee mobilization during the period of fixation when using the Ilizarov circular/hybrid frame (Figs. 15.7–15.9).

Insertion of the fixation elements must always commence from the side of the location of the known vulnerable neurovascular elements: due to the possible unexpected deviation of the wires or Shanz screws while they traverse the hard tissues of the limb.

Start the fixation procedure by inserting the thin wire in the supracondylar zone of the femoral bone. In keeping with these principles, this wire is introduced from the medial side in a lateral direction parallel to the articular line and also parallel to the surface of the operating table. Then the wire is fixed in the distal ring or 5/8 ring of the Ilizarov frame.

The most proximal half-pin is introduced generally into the bone at the level of the lesser trochanter. The assistant, holding the shin and foot, performs manual axial distraction in the rotationally aligned position and then the proximal half-pin is fixed to the proximal half-ring frame. A towel bolster is placed beneath the posterior surface of the thigh at the level of the intermediate rings to eliminate sagging of the bone ends in the fracture zone. Then fracture fragments distraction in the external fixation frame is performed. Additional resonating wires with olives (traction effect) and half-pins ("joystick" maneuvers) are introduced into the bone fragments; after achieving fracture reduction, they are fixed to intermediate ("unmarried") rings of the frame. Pin configuration, described by Catagni and Cattaneo ("Delta pattern"), and including one frontally oriented thin wire and two posteromedial and posterolateral half-pins with a 60° crossing angle on the distal femoral ring, provides good skeletal stability with the least soft tissue transfixation near to the knee joint.

The rigidity of the fixation frame itself is checked before performing the reduction procedure!

The classical circular frame introduced by Gavriil Abramovich Ilizarov used only thin wires. Half-pins have become more widely used as bone fixation elements in later generations of circular fixation frames, especially in femoral fixation frames. At the present time, most circular frames use half-pin fixation in the proximal part of the femoral bone and thin wires (or a combination of wires and half-pins) in the distal part of the femoral bone. Transfixation of significant muscle bulk is unavoidable when applying external femoral fixation and frequently causes restriction of movement of the knee joint, not only during the external fixation period, but also after removing the fixation

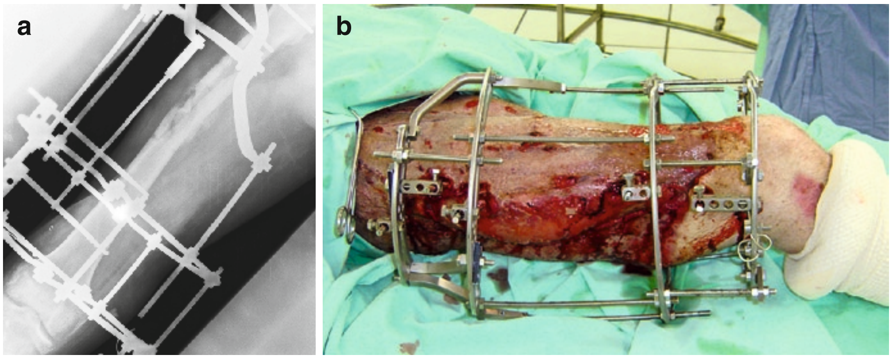


Fig. 15.7 (**a**) Clinical and (**b**) radiological appearance after stabilization of the complex open femoral fracture using Ilizarov external fixation frame, includes a distal ring and 5/8 ring and two proximally placed half-rings

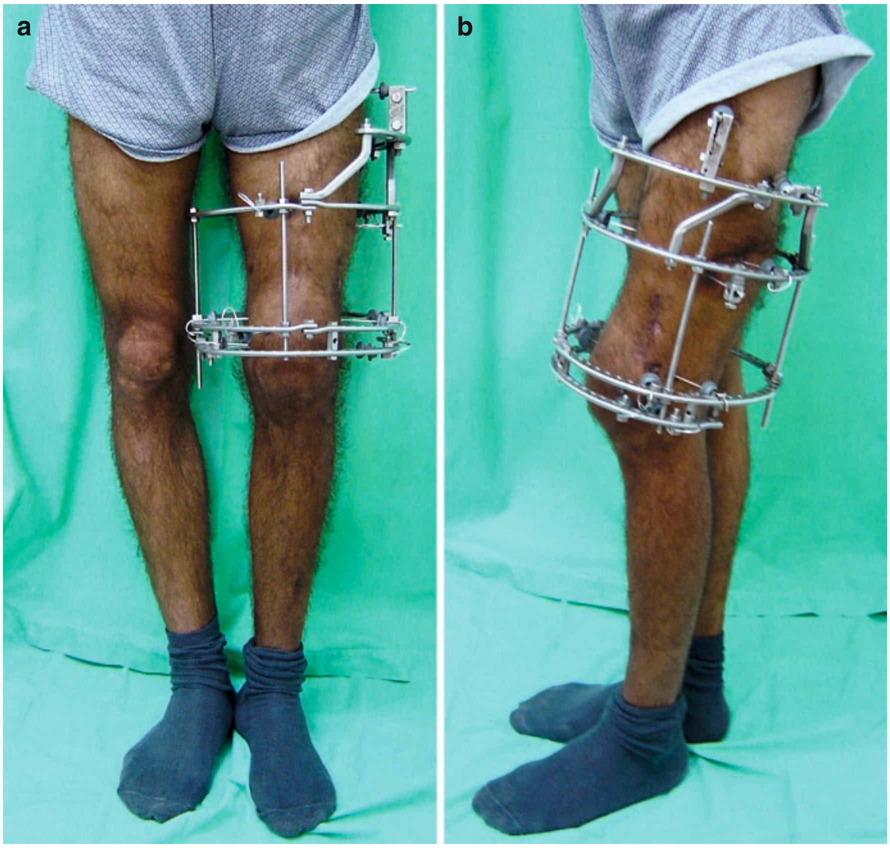


Fig. 15.8 (**a**, **b**) Clinical pictures demonstrate stabilization of open femoral fracture caused by GSW using Ilizarov external fixation frame, includes a distal ring and 5/8 ring and a proximally placed ring and half-ring

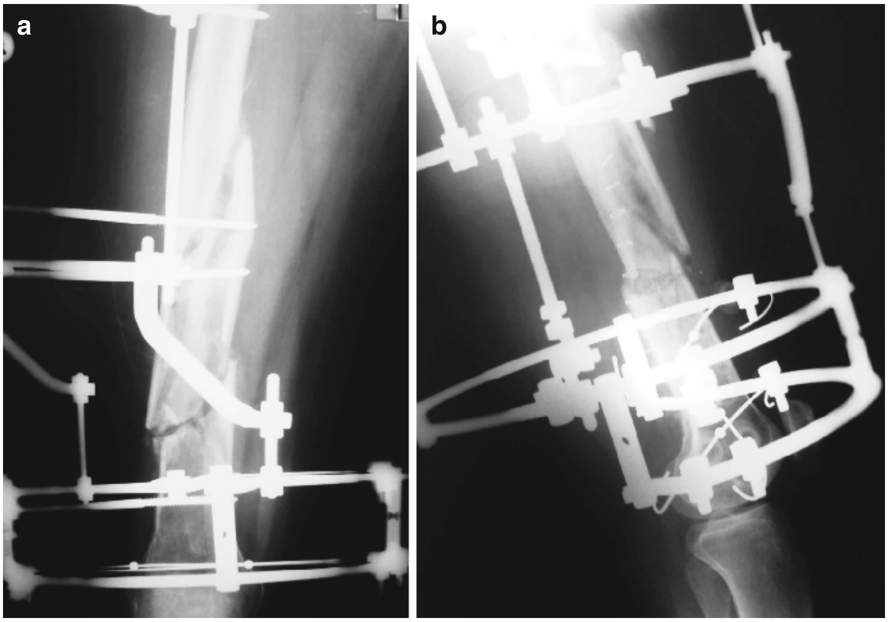


Fig. 15.9 (**a**, **b**) Radiological pictures demonstrate stabilization of distal femoral fracture using Ilizarov external fixation frame, includes a distal ring and half-ring and proximally placed two half-rings

frames. To prevent this severe complication, the following tactics are recommended:

1. Avoid insertion of the thin wires and half-pins through muscle-tendon units. The “Delta pattern” orientation of fixation elements, described by Catagni and Cattaneo, is the optimal configuration of the fixation frame near the knee joint.
2. When inserting thin wires near the joint line which cross from the extensor to the flexor surface, the knee must be flexed until the wire crosses the bone; then the knee must be extended during the passage of the wire through the flexors. This produces a definite reserve of soft tissues near the joint and diminishes mechanical obstacles to joint motion during the external fixation period.
3. Proper patient education of the need for early active and passive motions of the joints of the operated limb, along with early functional loading, including weight-bearing, must be instituted.
4. Effective analgesia in the postoperative period allows early functional mobilization.
5. Avoid prolonged fixed positioning of the limb, especially full extension or gross knee flexion. It is essential to preserve some flexion (10–15°) in the knee joint at all times, including during early postoperative limb elevation.

15.4.2.2 Tibia

When operating on the leg (calf), an elevation bolster is placed under the thigh, freeing the posterior aspect of the calf, thereby avoiding flattening of the calf under its own weight and the danger of excessive skin and soft tissue transfixation and the complications connected with it. The stabilization of the tibial fracture is commenced by the insertion of the proximal reference metaphyseal thin wire, which must be introduced from the anterolateral aspect of the shin (proximal or anterior to the fibular head) in a posteromedial direction in the plane of the articular surface of the knee.

The assistant, holding the foot, performs manual axial distraction in rotational alignment (visual and palpatory orientation of the foot and knee is mandatory; thus, the knee and ankle joints must remain uncovered throughout). The distal tibial bone fragment must be fixed in the distal ring of the frame using another reference thin wire inserted in the supramalleolar zone from the posteromedial site in the anterolateral direction. Insertion of both these wires is guided by intraoperative imaging; parallel positioning according to the knee and ankle joint line is desirable. Insertion of these para-articular wires in a position deviated from the joint lines can cause mal-angulation of the main bone fragments after tensioning and fixation of the wires onto the preassembled hard frame. A similar mal-angulation of the bone fragments can be observed by tightening the nuts on the threaded rods that are not in the correct perpendicular position relative to the corresponding rings. Sideways displacement of bone fragments can result after tensioning of obliquely inserted proximal and distal para-articular wires. A small deviation of thin wires from a plane parallel to the articular surface of the corresponding joint need not be an indication for reinserting the wire; this can be corrected by adding washers between wires and rings or by fixing the wire ends to the opposite side of the ring (accordingly to the deviated wire's deflection).

A towel bolster is placed between the posterior surface of the calf and the rings to eliminate sagging of the bone ends in the fracture zone, thereby preserving alignment. Distraction of the bone fragments in the frame is then performed (a slight overdistraction is desirable). Then, under radiological control, angulations or side displacements of the bone fragments can be corrected using one olive wire above the fracture site and another olive wire below attached to the corresponding intermediate rings of the frame. The opposite end of the olive wire must also be tensioned and fixed to the corresponding ring after performing translation of the bone fragment. The end of the wire closest to the olive should be marked by a rubber plug to prevent wrongly directed withdrawal traction during the final fixator removal procedure. We also recommend marking both ends of the olive wire differently because, during the prolonged period of external fixation, a single plug may fall off (Fig. 15.10).

Not only traction but also pushing of the olive wires can be used in some cases for bone fragment transposition. Then, after final positioning of this single bone fragment and its radiological verification, it can be transfixed to the nearby corresponding main distal or proximal fragment (Fig. 15.11).

Temporary bone fragment overdistraction, required at the stage of fracture reduction, must be corrected and released at the end of the operative procedure. The reverse, achieving some compression at the fracture site, is desirable for the treatment of patients with

Fig. 15.10 Clinical pictures demonstrate stable external fixation of high-energy tibial fracture using Ilizarov radiolucent carbon frame sufficient for early full weight-bearing. Note good wound coverage using free tissue flap (latissimus dorsi muscle)

non-comminuted fractures. *However, not only overdistraction of the bone fragments, but overcompression can also be a mistake*. Overcompression of oblique-shaped bone ends and overcompression of insufficiently stabilized bone fragments can result in an unwanted deformation.

15.5 Fibular Stabilization in Distal Tibiofibular Fractures

The method of minimal invasive fixation in circular/hybrid external fixation frames allows effective stabilization of severely comminuted complex fractures in the distal third of the tibial bone (including pylon fractures) and is well established in the treatment of these challenging injuries. Rigid fixation of the fibular bone by plating and screw is an obstacle in the use of the Ilizarov method; it abolishes its unique ability to exert an ongoing dynamic influence on the tibial bone fracture site. Rigid fixation of the fibula deprives the Ilizarov method of its multiple possibilities, converting it into a static external fixation device. Moreover, the potential of filling in a large bone defect and lower limb-length restoration using the method of callotasis is excluded by the presence of rigid fibular fixation. Open reduction and internal fixation of the fibula in tibial plafond fractures treated with external fixation that spans the ankle is associated with complications, and good clinical results may be obtained without fixing the fibula [43].

We recommend closed fibular bone repositioning in the Ilizarov circular frame, utilizing the method of ligamentotaxis with olive wires for reduction and fixation. When open fibular repositioning is needed, bone stabilization is best performed with intramedullary placed (antegrade or retrograde) thin rods or wires. We use a preconstructed circular fixation frame, consisting of a proximal block of two rings for tibial shaft fixation; one more distally placed free ring above the meta-epiphyseal level, and a foot ring. Distraction is performed between the tibial block and the foot ring for ligamentotaxis and realignment of the bone fragments. Transfixation of the bone fragments using thin wires connected to the intermediate meta-epiphyseal ring is performed after achieving radiological anatomical reduction. Additional olive wires are an effective tool for performing closed reduction of residual displacement of bone fragments.

15.5.1 Open Reduction and External Fixation

In patients in whom a closed fracture reduction attempt was unsuccessful, especially in treating displaced intra-articular fractures where precise anatomical reduction is needed, open reduction must be performed, keeping in mind the balance between the potential positive effects of precise articular reconstruction in very severe injuries and the potential complications of the open surgery, particularly in the presence of local soft tissue damage. A careful atraumatic technique that minimizes direct injury to the soft tissues during definitive fracture surgery is crucial [40]. This is facilitated when performing open reduction of the bone fragments in the presence of an external fixation frame, which allows a small surgical

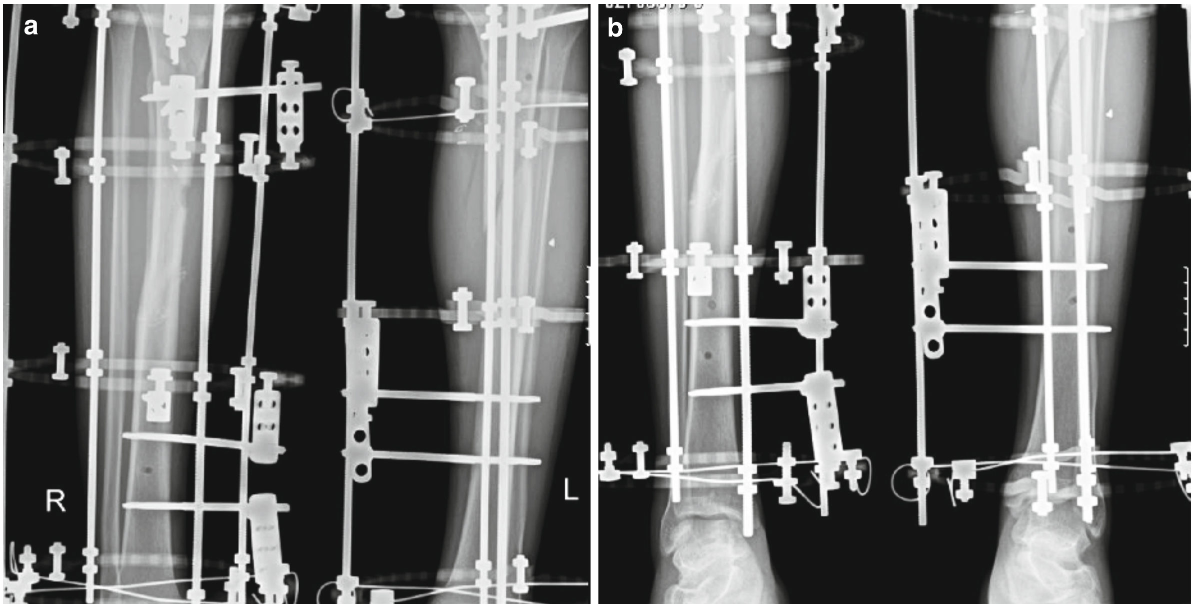


Fig. 15.11 (**a**, **b**) Radiographs demonstrate external fixation of bilateral tibial fractures in patient who suffered from blast injury to lower limbs, using classic four-ring Ilizarov frames (radiolucent carbon rings)

approach and, accordingly, is accompanied by less soft tissue traumatization. Distraction, ligamentotaxis, and axial alignment are by the frame itself. Also, the thin wires with olives assist the closed reduction in the external fixation frame to achieve final reduction (Fig. 15.12).

The surgeon should quickly pass on to the open fracture reduction when he realizes, after a few attempts, that closed reduction is unlikely to succeed.

Fracture reduction is simplified in treating patients having open fractures with exposed bone ends as compared to the reduction of closed fractures. Open reduction is performed in these patients through the wound in the final stage of debridement and maintained with clamps or by applying thin wires through the reduced bone fragments for temporary fixation to keep them in the aligned position. Then the preassembled frame is applied on the injured limb segment and thin wires and half-pins are introduced into the bone fragments according to the fracture configuration and soft tissue condition. The clamps and wires of the temporary fixation can be removed once stable fixation of the fragments in the circular/hybrid external fixation frame has been achieved.

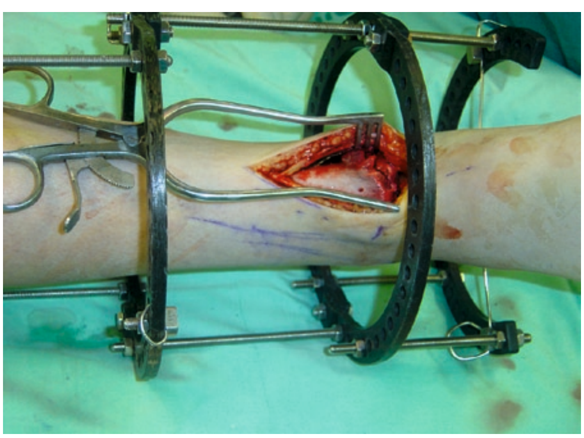


Fig. 15.12 Open reduction of pylon fracture, accompanied by distraction, ligamentotaxis, and axial alignment in the circular external fixation frame

The wire, used for the stabilization of separate bone fragments must not be fixed to the ring which is connected to one of the main bone fragments, if you plan to perform compression (or distraction) between these intermediate and main fragments in the future.

In the presence of good soft tissue coverage over the bone fragments and fracture site, it is possible to augment external fixation by fixing a single major bone fragment using additional cannulated screws. To prevent the spread of superficial pin-tract infection and its extension into the deep tissues and bone around the implanted screws, contact between screws and thin wires or half-pins of the external fixation frame must be avoided (Fig. 15.13).

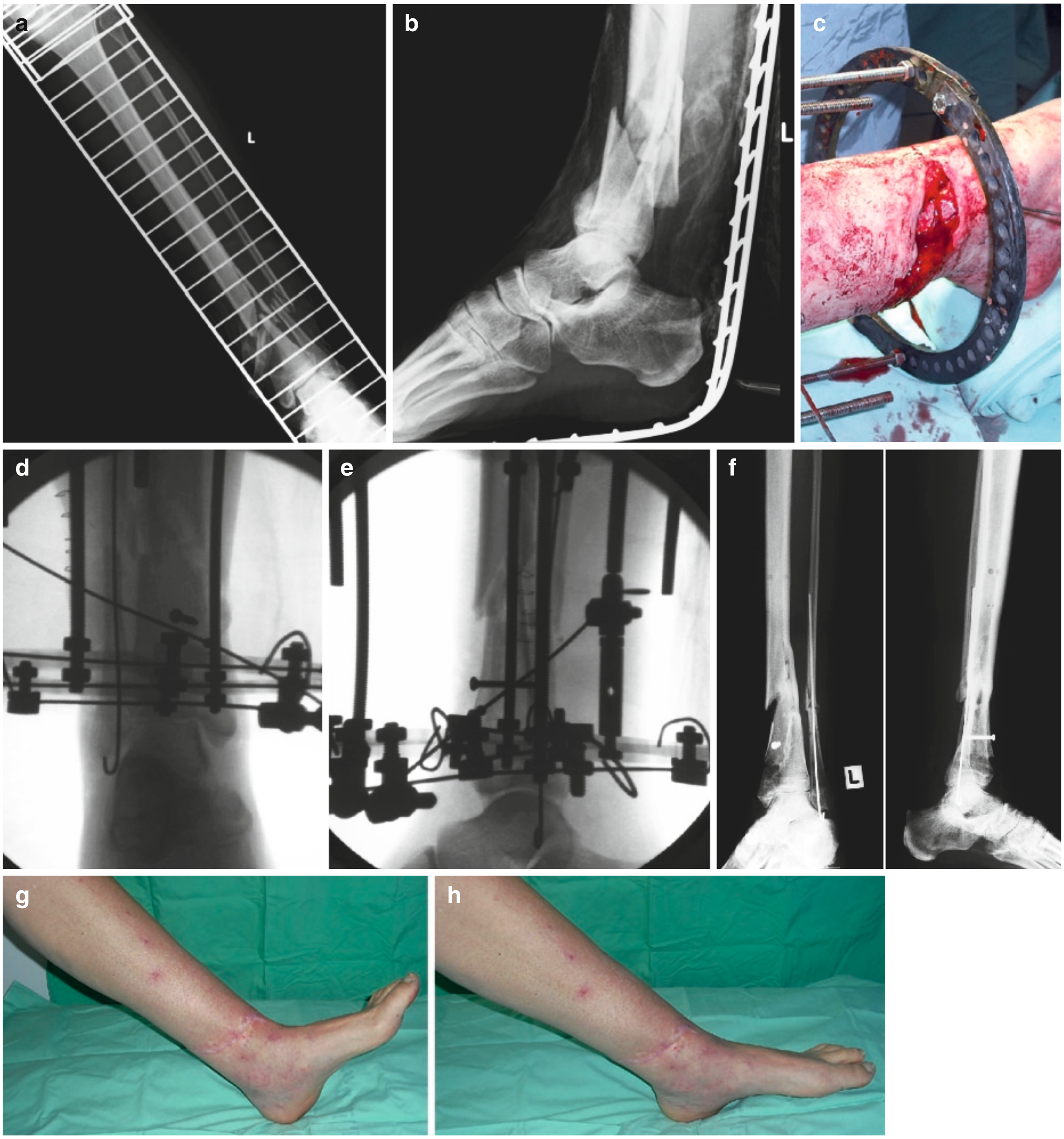


Fig. 15.13 A 43-year-old female sustained an open fracture of the left distal tibia with severe bone comminuting. (**a**, **b**) Radiological pictures demonstrate displaced fracture with severe comminuting of distal third of the left tibia. (**c**) Surgical exploration and debridement of the wound were performed. Clinical view after debridement of the wound and minimal internal fixation of the large bone fragment during fracture stabilization in the circular Ilizarov frame. (**d**, **e**) Intraoperative radiological pictures after performing intramedullary fixation of the fibular bone using a thin nail and Ilizarov external fixation of the tibial bone. Note single intra-fragmental screw in the tibial bone without contact with implanted elements of external fixation frame. (**f**) Radiological pictures at half-a-year follow-up demonstrate solid bone consolidation in good alignment. (**g**, **h**) Clinical pictures demonstrate ankle joint ROM at follow-up half-year after removing the external fixation frame

15.5.2 Bilateral Lower Limb Injuries

Bilateral lower limb injuries, often encountered in severe high-energy trauma, enforce long periods of bed rest. The patient can only mobilize himself or herself early if the fracture fixation succeeds in enabling full weight-bearing on at least one of the injured limbs. The stability of fixation in the circular Ilizarov frame is usually sufficient to allow full weight-bearing on the injured limb, even in the presence of major bone loss. Stable external fixation of at least one of the limbs in the Ilizarov frame allows mobilization and early weight-bearing on this limb with crutches. This affords a basis for the functional treatment of the contralateral injured leg.

Bilateral injury to the lower extremities that results in amputation of one leg and limb salvage surgery on the other is a situation of unusual complexity, and one that requires surgeons to use considerable foresight in determining treatment strategies. The Ilizarov external fixation device is indicated in limb salvage when contralateral amputation is present, as it fulfills the criteria for early amputee rehabilitation while simultaneously achieving cyclic loading that facilitates fracture healing in the residual limb. *The patient's capability to bear full weight on the limb, fixed using a circular external fixation device, allows the unimpeded independent and concomitant adjustment of the prosthesis to the stump of the contralateral limb* (Fig. 15.14).

15.5.3 Primary Circular/Hybrid Fixation Frame Assembly

After severe trauma, it is sometimes possible to perform the definitive precise reduction and fixation of the bone fragments as the primary surgical procedure, avoiding the need for a secondary operative orthopedic procedure. This can only be done if the patient's

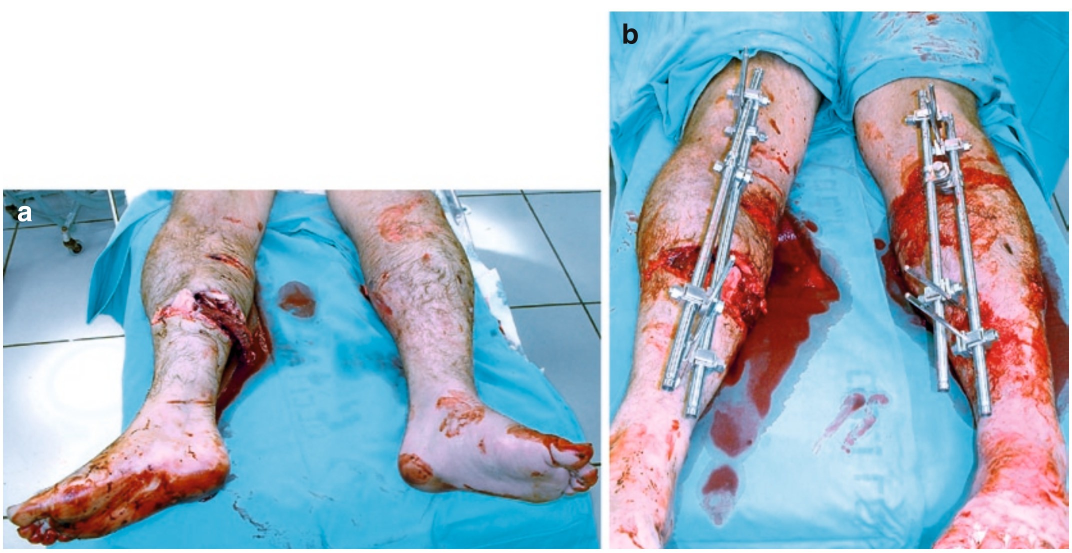


Fig. 15.14 A 25-year-old male sustained bilateral lower limb injury with open Gustilo–Andersen type IIIA fractures of left tibia and severe crush injury right leg with incomplete amputation. Extensive wound debridement at the open fractures and fasciotomy were performed. Primary skeletal stabilization of both the legs was achieved using unilateral external fixation frames. Right leg was amputated 7 days latter due to ischemic necrosis. (**a**) Clinical picture of the lower limbs at admission. (**b**) Axial realignment and external fixation were performed on admission in high-energy compound tibial fractures for emergency stabilization. (**c**) Radiological picture demonstrates external fixation of left tibial fracture. (**d**, **e**) Radiological appearance after conversion of the unilateral tubular frame to the Ilizarov frame demonstrates good axial alignment of the multi-comminuted tibial fracture. (**f**) Clinical photo demonstrates full weight-bearing using walker at the early postoperative period. (**g**) Clinical picture demonstrates good soft tissue healing at left leg after skin grafting, preparation of right leg stump for prosthetic fitting. (**h**) After removing the Ilizarov external fixation frame, the patient continues rehabilitation process with full weight-bearing on left leg, protected by hinged brace for additional 5 months; right leg was fitted with prosthesis. (**i, j**) Radiological appearance at a 1-year follow-up demonstrates bone healing of left tibial fracture in good axial alignment

Fig. 15.14 (continued)

general condition is stable and concomitant life-threatening injuries are absent. The blood supply to the limb must be adequate: vascular repair can be impeded by a circular frame around the injured limb. Equally, the treatment of soft tissue defects, demanding local or free tissue transfer for the coverage of the wound, is obstructed by circular fixation. The absence of a well-trained expert in the Ilizarov method is also an absolute contraindication to the performance of a technically difficult procedure at the primary stage of treatment of a severe limb wound.

Application of the circular Ilizarov device can be performed in stages. A circular frame may be used at the stage of primary limb stabilization similar to the commonly used unilateral fixation frame. Such a frame contains only two proximal and distal rings, or even four classical rings, limiting primary fixation of the bone fragments only to most proximal and most distal rings. Fracture stabilization in the alignment position is the only aim in this first emergency stage of treatment. The fixed limb is suspended in the circular frame at an elevation, maintaining not only the fracture stabilization but also protecting the skin and soft tissues on the inferior surface of the limb from any pressure. A specific indication for primary stabilization of the bone fragments using a circular or hybrid external fixation frame is immediate bone fixation in patients suffering from complex fractures combined with extensive damage or loss of skin and soft tissues on the posterior surface of the injured limb. The next stage is the secondary final precise reduction and stable fixation of the bone fragments in the circular frame, and this is performed only after stabilization of the patient's general and local condition: this involves upgrading of the frame to the optimal construct. The modularity of the circular/hybrid fixators permits the construction of an appropriate customized frame (Fig. 15.15).

15.5.4 *Hinged Fixation of Extensive Periarticular Injuries*

Severe trauma to the major joints, especially the knee and the elbow, is common in modern war injuries [28]. These high-energy injuries are usually associated with massive soft tissue damage and ligament and capsular tears [42]. Reliable stabilization of the periarticular bone fragments enabling simultaneous early motion optimizes the functional outcome of these complex injuries.

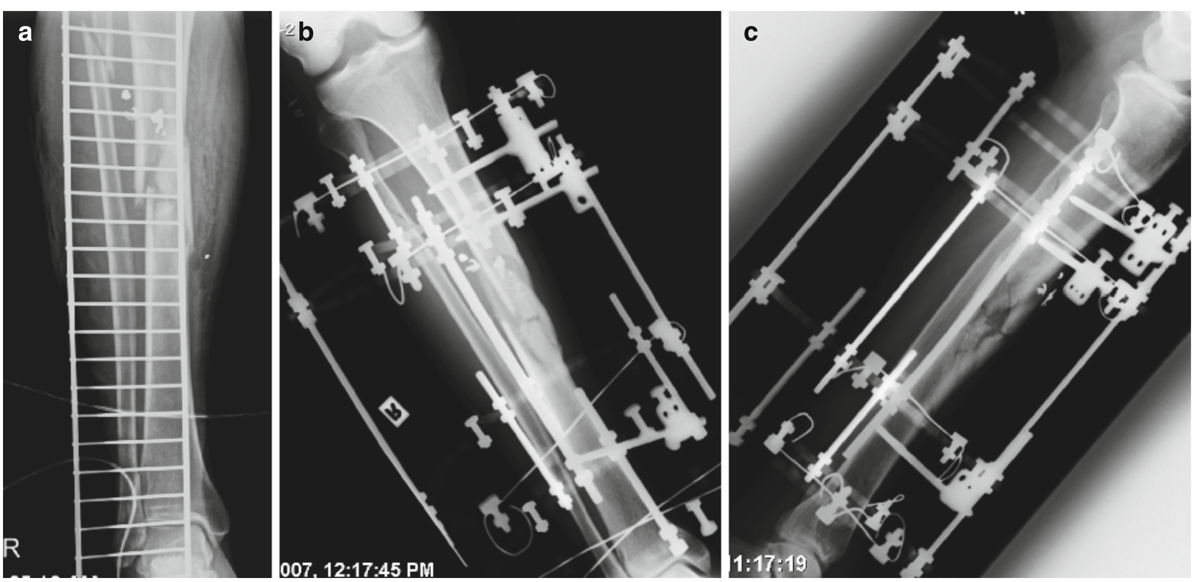


Fig. 15.15 A 36-year-old male, victim of a blast injury who sustained an open comminuted fracture of the right tibia. (**a**) Radiological pictures demonstrate comminuted fracture of the right tibial bone. (**b**, **c**) Debridement and primary external stabilization using Ilizarov circular frame were performed. Radiological pictures demonstrate acceptable position of the bone fragments, multiple foreign bodies (shells) in the fracture region. (**d**) Radiological pictures at a 1-year follow-up demonstrate solid bone consolidation in good alignment. (**e,f**) Clinical pictures demonstrate full knee ROM at a 1-year follow-up after removing the external fixation frame

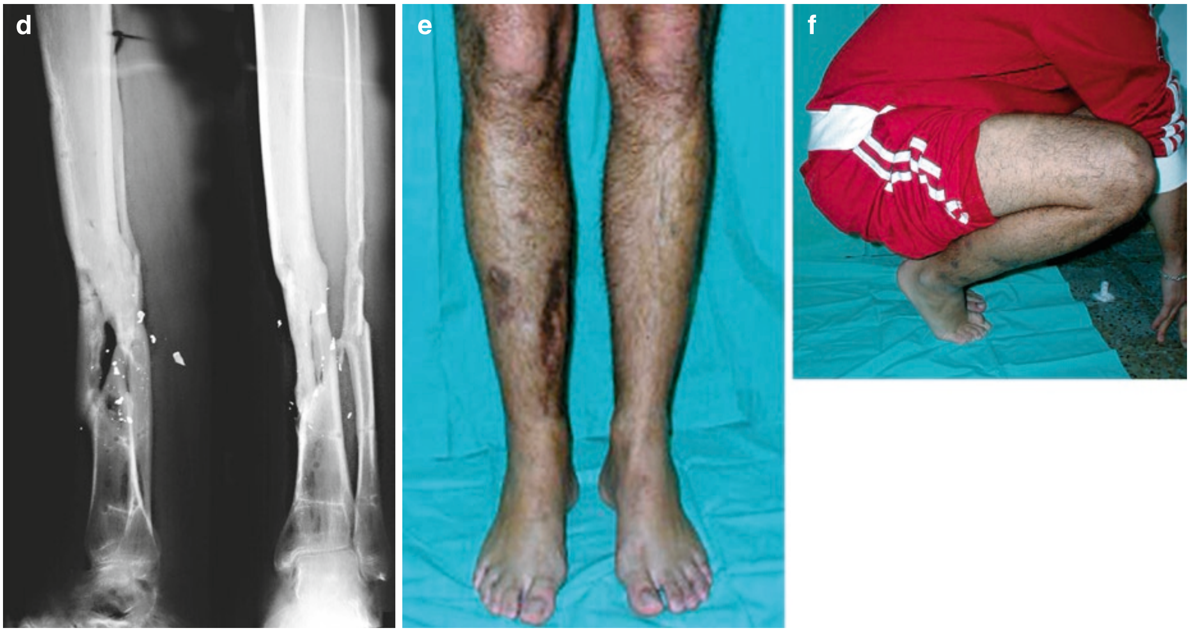


Fig. 15.15 (continued)

This early mobility will result in less joint stiffness. The combination of stability with motion is provided by the modular circular/hybrid external fixation frame.

Only after stable fixation of the periarticular fracture (before bridging) can the joint be physically and radiologically examined for occult ligamentous and capsular injuries. Unstable knee, elbow, or ankle joints are first managed by external fracture fixation from both sides of the joint, connected by hinges that provide lateral stability and enable immediate function.

We recommend trans-articular hinged external fixation not only after periarticular fractures, but also for patients with massive periarticular soft tissue injuries due to high-energy trauma.

When adequate fracture fixation is not achieved (multi-fragmental fractures or extremely short periarticular fragments), and also for severe damage to the joint capsule and ligaments, it is necessary to use prolonged bridging-dynamic fixation: after finishing the definitive reduction and fixation of the fracture, the threaded rods of the temporary bridging-rigid articular fixation are changed to hinged rods, placed in the axis of articular motion. The mechanical proprieties of such a modular dynamic external fixation frame allow the temporary limitation of the range of motion according to the requirements of the level of stability, condition of the wound, and tendomuscular and neurovascular damage.

The hinges are usually applied to both the lateral and medial sides of the injured joint. This is helpful if a high degree of stability is needed. The most important step in assembling the trans-articular hinged fixation is the proper placing of the axis for articular motion. This is a technically demanding procedure and requires accurate anatomical placement of the hinges. A mistake in the setting of the hinge axis creates displacing forces, causing further damage to the articular cartilage by overcompression or damage to the ligamentary complex by overdistraction. In addition to carefully observing the anatomical landmarks, we do not primarily attach the hinge firmly to the corresponding ring, but observe the hinge during articular motions. Declination of the hinge from the ring during these articular motions indicates an incorrect selection of the axis of movement of the joint. This dynamic test must be repeated after changing the location of the hinge. The absence of displacement of the hinge during joint movement is a good indicator for the accurate selection of the axis of motion. Only then should the hinges be firmly fixed to the corresponding proximal and distal rings. Then the same procedure is repeated from the opposite side of the transfixed joint (Fig. 15.16).

Fig. 15.16 A 23-old male who suffered from comminuted tibial plateau fracture of left knee and acute compartment syndrome. (**a**, **b**) Radiological pictures on admission demonstrate multi-comminuted tibial plateau fracture. (**c**) Immediate fasciotomy was performed and the fracture stabilized using bridging tubular external fixation frame. Radiological picture demonstrates knee-joint bridging stabilization. (**d, e**) Ten days later, conversion to trans-knee hinged Ilizarov external fixation frame was performed. Due to presence of post-fasciotomy wound irritation, closed fracture reduction achieved using ligamentotaxis and olive wires as pull and pushers. (**f**, **g**) Radiological pictures at 2-year follow-up demonstrate solid fracture healing. (**h**, **i**) Clinical pictures at a 2-year follow-up demonstrate 0–90° ROM of left knee joint

Fig. 15.16 (continued)

Some articular distraction must be preserved with the hinges to prevent the articular surfaces from damaging each other by compression of the joint cartilage and prevent displacement of the intra-articular bone fragments during weight-bearing.

Contrary to some existing configurations of external articular hinged fixation frames, we do not use articular axial wires. There are no pins within the joint, reducing the risk of joint irritation and infection [26]. Therefore, we justify the use of an axial articular wire only if it is absolutely necessary for the mechanical fixation of intra- or periarticular bone fragments.

ROM exercise is instituted as tolerated, avoiding the pain of muscle spasm. Restoring articular motion requires much effort, time, and strong motivation of the patient. Moreover, transfixation of soft tissues in the external fixation frame restricts movement in the adjacent joints, which will remain until the transfixing elements are removed.

The necessity for trans-articular fixation recedes during consolidation and maturing of the fracture callus. Then the ring on the opposite side of the joint and the hinges can be dismounted. External fixation of the fracture itself is continued until fracture consolidation is sufficient.

15.5.5 Peculiarity of Upper Limb Reconstruction: Methods of Isolated Hybrid External Fixation of the Humerus, Ulna, and Radius

The elbow is the most susceptible joint of the upper limb to war injury [1]. These fractures are often unstable, having intra-articular and/or periarticular components. The destroyed elbow is characterized by a global injury to bone and soft tissue [6]. Surgical reconstruction of elbow fractures is difficult because of the complex anatomy of the joint and the need to begin postoperative motions as soon as possible [44]. Associated soft tissue injuries, fracture type, and degree of bone comminution are the main factors that dictate the type of fixation. The elbow joint has a poor potential for good function following high-energy intra- and juxta-articular fractures, in spite of good anatomical realignment [28, 44]. Prolonged elbow immobilization also leads to joint stiffness and poor function.

The specific anatomical locality of the fracture necessitates some special steps for optimal fixation.

The neurovascular topography dictates the strict abidance of safe zones during the insertion of thin wires and half-pins to the bones. As a rule, a pair of half-pins into each side of the fracture is enough for primary fixation of bone fragments.

Distal humeral fractures and severe intra-articular elbow fractures need temporary articular bridging. Proximal half-pins introduced into the bone at the level of the proximal and mid-third of the humeral bone, and application of proximal pins of the external fixator through the humeral head are needed in extended comminuted humeral shaft fractures [3]. A distal half-pin should be introduced at the level of the proximal third of the ulnar bone. The relatively small diameter of the ulnar bone in the mid-third demands the use of small-diameter half-pins to prevent iatrogenic fractures. Primary fixation on the forearm level in patients with comminution of the proximal ulnar bone is done by insertion of half-pins to the distal radial bone. Such a frame provides relatively lesser stability of fixation due to the comparatively long distance between the proximal and distal pairs of half-pins. Therefore, these configurations demand earlier conversion to a final fixation frame. Additional fixation of the forearm bones using mini-external fixation sets is used in treating patients with multiple comminuted fractures.

In the humerus, use primary half-pins when performing conversion of the primary tubular external fixator to the circular frame (as long as their localization is accurate, their stability is good, and there are no local soft tissue problems). It is necessary to insert a third half-pin or thin wire in some patients to increase stability of fracture fixation. External fixation of the distal humeral fragment is technically difficult. Use two thin olive wires, inserted through the internal and external humeral epicondyles. An additional half-pin, located more proximally and inserted through the posterior bone surface, provides sufficient stability to the fixation of the distal bone fragment. Overdistraction separating the bone fragments must be recognized and avoided during the finishing touches of fracture fixation, because this can significantly extend the time of bone healing and external fixation in the frame. The likelihood of nonunion is also increased. In contrast, some shortening of the united humeral bone will not adversely affect future upper limb function. Using commercially available hinged elbow external fixators is technically demanding [39]. The most critical step is the correct placement of the axial pin. Care must be taken to protect the ulnar nerve during insertion of the axial pin. In contrast, the Ilizarov external fixator provides for mounting a hinged frame without needing the precisely inserted and potentially dangerous axial wire.

In treating patients with extensive multi-comminuted fractures of the humeral bone, it is possible to perform closed reduction and sufficient fixation in the acceptable alignment using the hybrid external fixation frame as “a mobile skeletal traction device” with a minimal number of inserted thin wires and half-pins. Two or three half-pins are inserted to the proximal main fragment of the humeral bone. Only one distally placed thin wire, introduced through the olecranon in the coronal direction, is sufficient to allow closed reduction of the bone fragments, using the method of ligamentotaxis. Moreover, this provides early functional mobilization of the elbow joint [17].

In forearm injuries, it is important to preserve pronation/supination motions during the period of external fixation [44]. This requirement can be guaranteed only by utilizing separate bone fixation for each of the forearm bones. To solve this problem, fixation of the forearm bones is done using a pair of *separate* unilateral frames, circular frames, or hybrid fixators. We prefer separate fixation of forearm bones in two hybrid external fixation frames. The ring (or half-ring) is placed over the distal fragment of the radius and attached to the bone using thin wires and half-pins. The unilateral part of this fixator is placed over the proximal radial fragment and fixed to the bone using two or three thin half-pins.

Stabilization of the ulna is performed in the reverse order: a half-ring is positioned over the proximal bone fragment (and fixed using thin wires and half-pins), while the unilateral part of the frame is attached to the distal bone fragment using small-diameter half-pins. This method of fixation of forearm bones allows rotational motions during the period of external skeletal fixation. “Heroic” attempts to force the severe complex fracture into the “procrustean bed” of the standard available fixation frame must be discarded. Active and assisted passive motions should be initiated on the second postoperative day (Fig. 15.17).

The upper limb has a high potential for healing and regeneration due to its rich blood supply and the absence of weight-bearing loading required for the lower limb. Functional restoration is likely, even in patients with very severe injuries. According to the literature, a primary neurological deficit after gunshot wounds to the upper limb resolves in time in 70% of patients without any specific intervention [19] (Fig. 15.18).

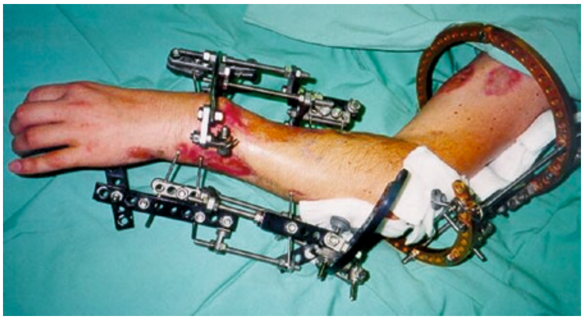


Fig. 15.17 Isolated hybrid external fixation of humeral, ulnar, and radial bones after blast injury to left upper limb

15.5.6 Primary Arthrodesis for Joint Destruction

Extensive articular and periarticular destruction make surgical salvage impossible. Arthrodesis as an alternative to limb amputation has many functional and psychological benefits. Primary arthrodesis is advocated as a treatment for severe intra-articular fractures with severe tissue loss [1, 7]. When the articular surface is destroyed,

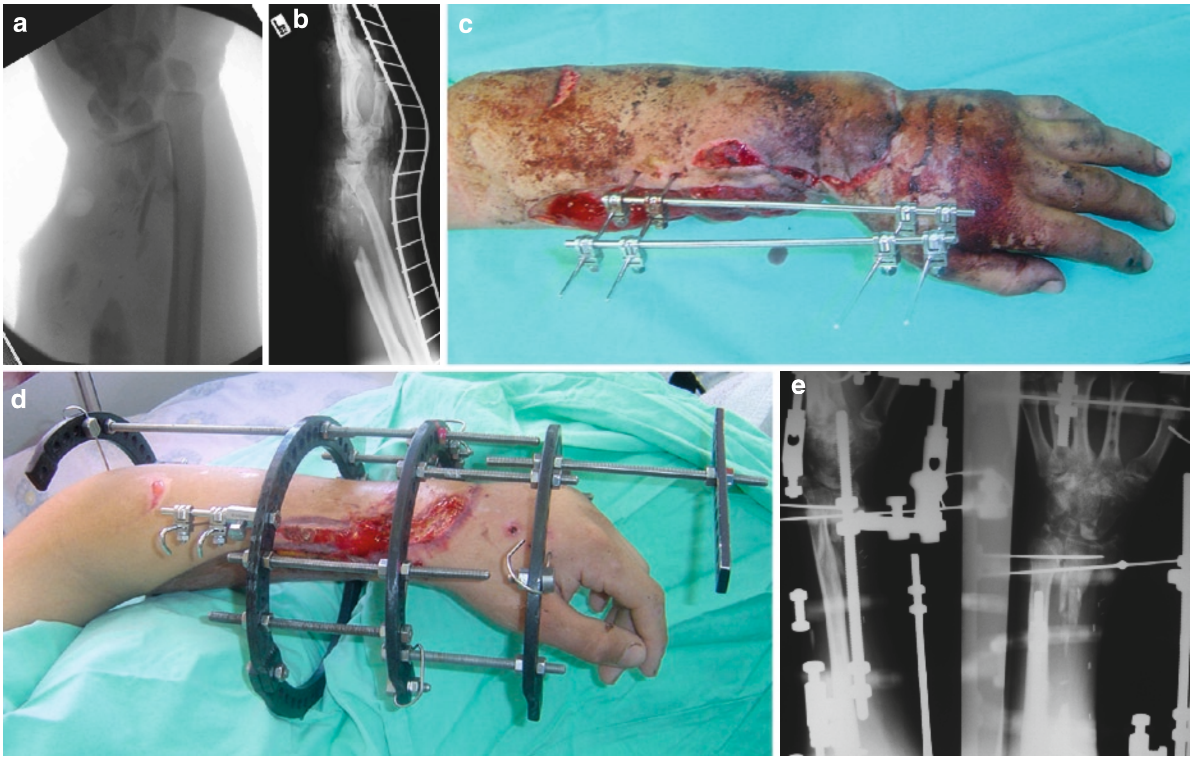


Fig. 15.18 A 21-year-old male with blast injury to left upper limb. Gustilo IIIC radial bone fracture with severe bone and soft tissue loss. (**a**, **b**) X-ray on admission demonstrates comminuted intra-articular distal radial fracture with severe bone loss. (**c**) Clinical pictures after primary tubular external fixation demonstrate extensive skin and soft tissue loss. (**d**) Closed reduction of articular surface with external fixation in Ilizarov frame was performed. Clinical picture after skin grafting and conversion to Ilizarov frame. (**e**) Gradual restoration of radial bone length in the Ilizarov frame was started. Control x-ray demonstrates reduction intra-articular bone fragments with relative shortening of the radial bone. (**f**, **g**, **h**) Clinical pictures demonstrate early wrist mobilization in the hinged Ilizarov frame. (**i**, **j**) Free microvascular bone grafting (fibular autograft) was performed after restoration of radial bone length in the Ilizarov frame. (**k**, **l**) X-ray and clinical pictures at a 1-year follow-up demonstrate bone healing after bone grafting of the radial bone defect with good functional ROM

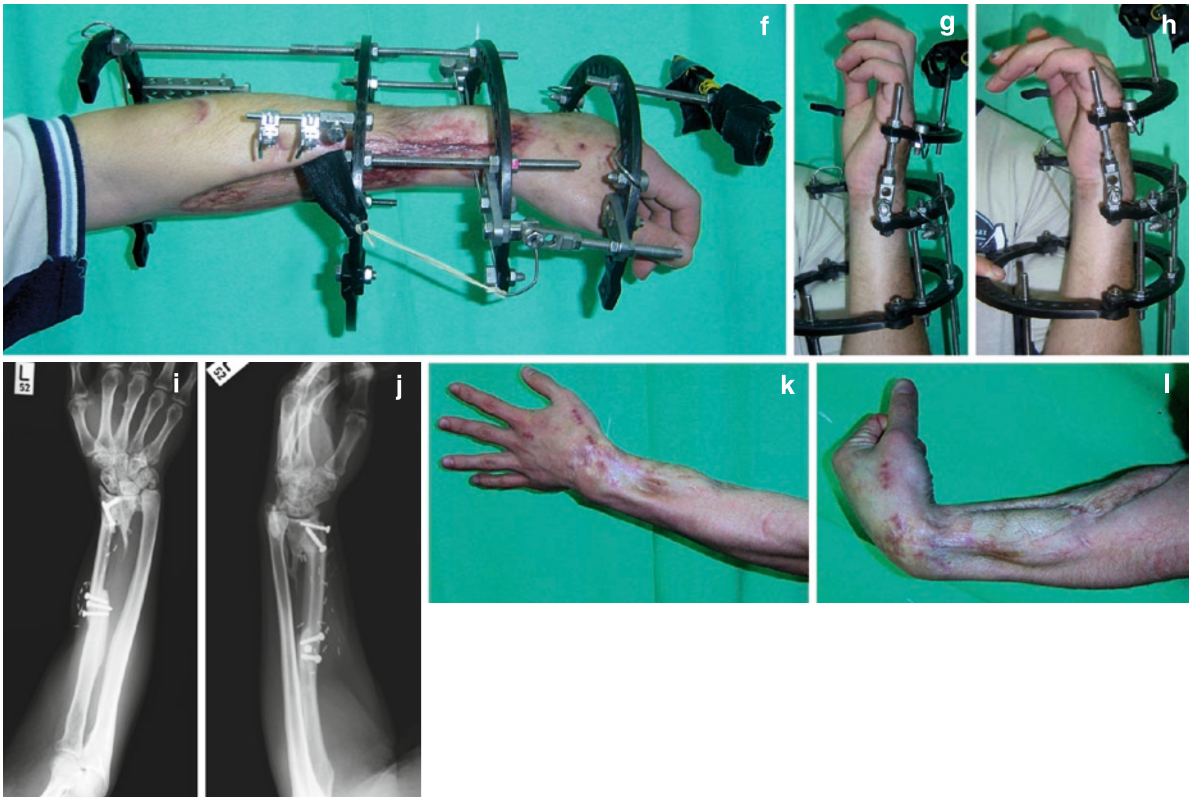


Fig. 15.18 (continued)

the external fixator maintains length and stability during the consolidation of an arthrodesis site [44].

A multitude of different methods of arthrodesis have been described. Large joints are not easily fused and most reported techniques have complications (nonunion, infection, and malunion). In the face of severe and extensive bone loss, inadequate soft tissue coverage, contamination and the presence of foreign bodies, the use of internal fixation is precluded. Residual cartilage must be excised and meticulous surgical debridement of all non-vital tissues must be performed. The Ilizarov external fixation frame stabilizes the bone and the wound while simultaneously performing arthrodesis of the destroyed joint. The hybrid/circular external fixation is assembled and customized in order to achieve the desired alignment and compression across the fusion site.

When properly applied, the Ilizarov/hybrid frame provides stable immobilization of the joint in three planes with stable fixation against shear and torsion stress, while axial loading is allowed without detrimental effect on the fusion site [11]. This versatile apparatus is highly modular and provides three-dimensional control over bone and joint deformities and instabilities. The frame is usually tailored for the particular patient and may be used for shortening, lengthening, compression, distraction, and bone transport. These parameters are determined intraoperatively but may be repeatedly and reversibly refined postoperatively throughout the healing process in order to eliminate any residual deformity.

Furthermore, this configuration of circular thin wire frames minimizes surgical invasiveness and provides the surgeon with remote control over the fusion process during the immobilization period. Joint resection is performed using standard techniques. Then the joint to be fused is temporarily stabilized using two crossed transosseous wires (half-pins). Begin by mounting the external fixation frame with the insertion of a pair of thin wires around the arthrodesis site: one wire from the each side of the joint. The open operative wound allows the insertion of the wires at the required distance from the arthrodesis site and in the correct direction, with a minimal expenditure of time and radiation exposure to the patient and the surgical team. These wires are fixed to two rings connected together with threaded rods. Thereafter the wound is partially closed, leaving a small opening for visual and palpation control of the arthrodesis site during assembly of the fixation frame. This technique has some advantages in comparison with the commonly recommended technique of apparatus assembly following skin closure. The first-inserted pair of the thin wires serves as a reference point for insertion of the following wires and half-pins during final mounting of the frame. The placement of the proximal and distal rings (or half rings) of the frame at a distance from the arthrodesis site increases stability of fixation. The final closure of the wound and arthrodesis site is performed by placing the last two to three sutures in the skin, whereupon additional thin wires and half-pins are inserted from each ring to further stabilize the fixation frame. The operative procedure is concluded by removing the temporarily placed wires and transfixing the arthrodesis surfaces. Compression of the arthrodesis bone surfaces is now performed.

All wires and half-pins are situated extra-focally and, therefore, further damage to the involved tissue is avoided. In patients with severe shortening due to trauma tissue loss or as a result of extensive articular surface resection, limb-length restoration by distraction osteogenesis at the site of the fusion or at the site of an additional elongation corticotomy/osteotomy can be performed.

The method of the limb-length restoration by distraction osteogenesis at the site of the arthrodesis after 20–30 days of compression has been recommended [5, 21]. This technique, in cases of war and other severe high-energy injuries, is not applicable because of the low potential for distraction osteogenesis in the compromised tissues in the zone of injury. Bone elongation is achieved more easily and safely away from the injury site.

Micromovements in the axial plane stimulate bone formation and enhance osseous healing [14]. Hence, early ambulation and weight-bearing are encouraged and may be initiated almost immediately. Permanent compression in the arthrodesis zone must be maintained during the entire period of fixation in the external frame. After frame removal, all lower limbs are protected in a POP walking cast (Fig. 15.19).

In patients suffering from high-energy injuries to the elbow joint with extensive bone and soft tissue loss, complicated by local infection, all options of surgical reconstruction are precluded, including total elbow arthroplasty. Elbow arthrodesis serves as a salvage option. The modular external fixation frame can be tailored to provide adequate skeletal stabilization in a preferred elbow position for fusion. Gradual sequential adjustment of the frame to 90° flexion can be used in treating patients with severe soft tissue loss, avoiding the need for additional complex skin flap procedures by gradual diminution of the soft tissue defect (Fig. 15.20).

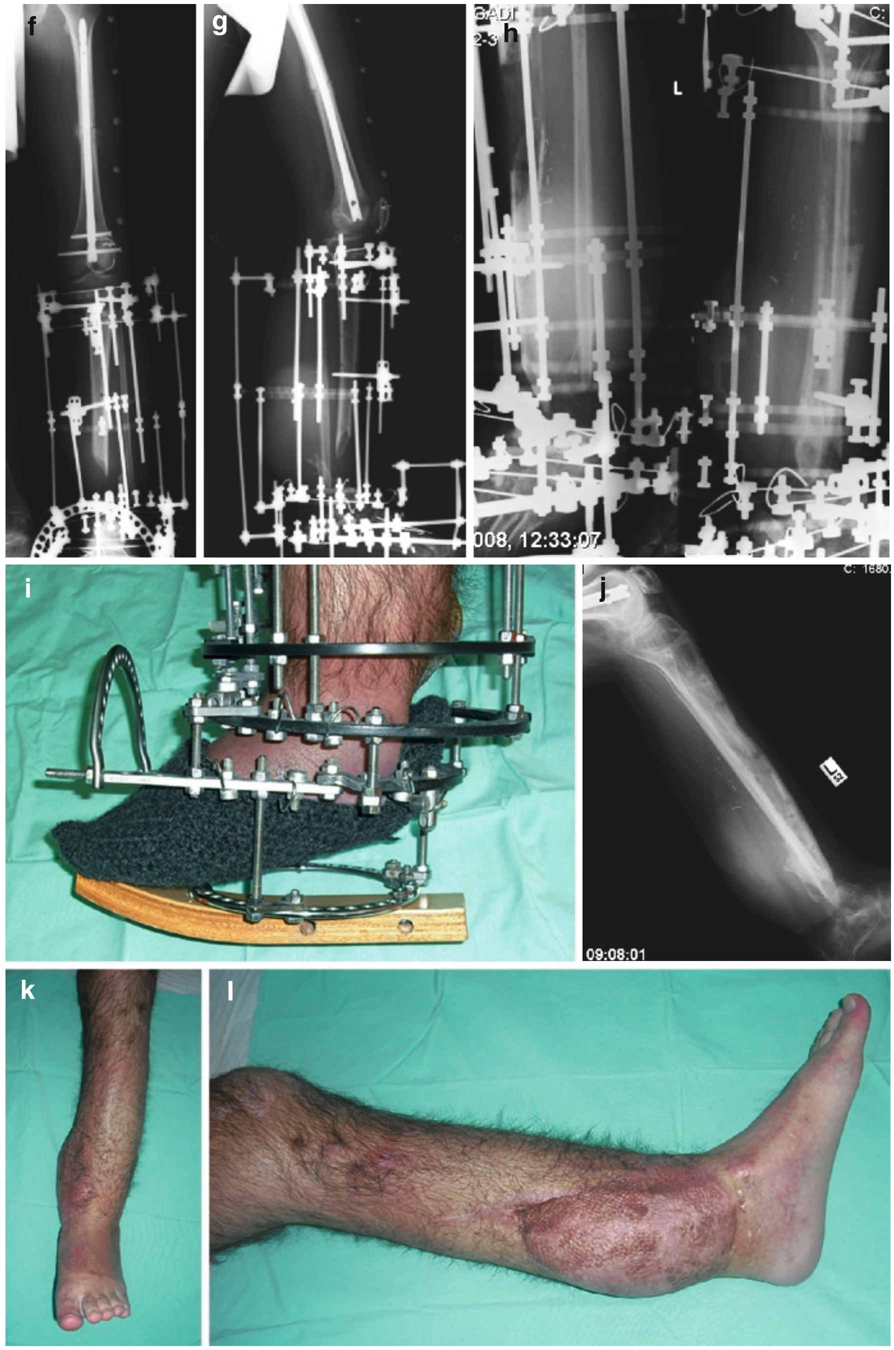
15.5.7 Limb Salvage in Severe Bone and Soft Tissue Loss

15.5.7.1 Bone Reconstruction by Callotasis (Bone Induction at the Site of Injury)

High-energy limb trauma may be accompanied by extensive bone loss. Bone loss may occur from extrusion of bone fragments at the time of injury, during debridement of the open fracture when devitalized segments of the bone are removed, or as a result of a combination of both, thereby creating a defect [12]. Severe damage to or loss of soft tissues complicates the healing of bone loss. Especially in the treatment of combat trauma (gunshot wounds and blast injuries), foreign bodies are present in the tissues, increasing the hazard of post-traumatic local sepsis. All these factors increase the likelihood of failure of bone grafting. In contrast, the method of controlled gradual distraction of bone fragments stabilized and fixed in the external fixation frame utilizes the osteogenic properties of the existing bone, not only for the fracture healing process, but also for the appropriate filling of the bone defects. Soft tissue tension during distraction in the frame also has some stabilizing effect on the overall fixation system. Callotasis is successfully utilized in elective orthopedics for limb elongation using osteotomy or corticotomy, and also for restoring the length and shape of the bone in the treatment of fractures caused by low-energy trauma in the presence of adequate blood circulation in the fracture zone. However, severe high-energy limb trauma, especially crush injuries and war trauma, resulting in the destruction of

Fig. 15.19 A 24-year-old male who suffered from open left distal tibial fracture-dislocation with severe bone loss resulting from crush injury. (**a**, **b**, **c**) Clinical and radiological pictures on admission demonstrate open fracture-dislocation of the left ankle joint with severe tibial bone loss. (**d**) Lateral radiogram on admission demonstrates ipsilateral femoral and patellar fractures. (**e**) Primary intramedullar femoral nailing and tension-band-wire patellar fixation were performed, left ankle joint was realigned and transfixed using tubular external fixation device with trans-ankle rod augmentation. (**f**, **g**) Two weeks later, distal articular bone fragment was removed due to tissue necrosis. Conversion to Ilizarov external trans-ankle fixation was performed. Radiological appearance of left lower limb after intramedullar femoral nailing, tension-band-wire patellar fixation, and trans-ankle Ilizarov external fixation. Note significant tibial bone loss. (**h**) Four weeks later, proximal tibial corticotomy was performed to eliminate distal tibial bone defect using bone transport technique. X-ray taken 4 months after corticotomy demonstrates tibial bone transport (11 cm) with incorporation of distal tibial bone end into talar bone. Note relatively weak bone regeneration. (**i**) Early full weight-bearing was allowed during entire period of stabilization in the external fixation frame. Clinical appearance of custom curved foot plate attached to the foot ring of the frame. (**j**) Ilizarov frame was removed after 15 months of external fixation. After removing the Ilizarov frame, functional loading was continued using walking brace. Radiological appearance of solid bone regeneration. (**k**, **l**) Clinical appearance at a 1-year follow-up after removing the Ilizarov fixation frame

Fig. 15.19 (continued)



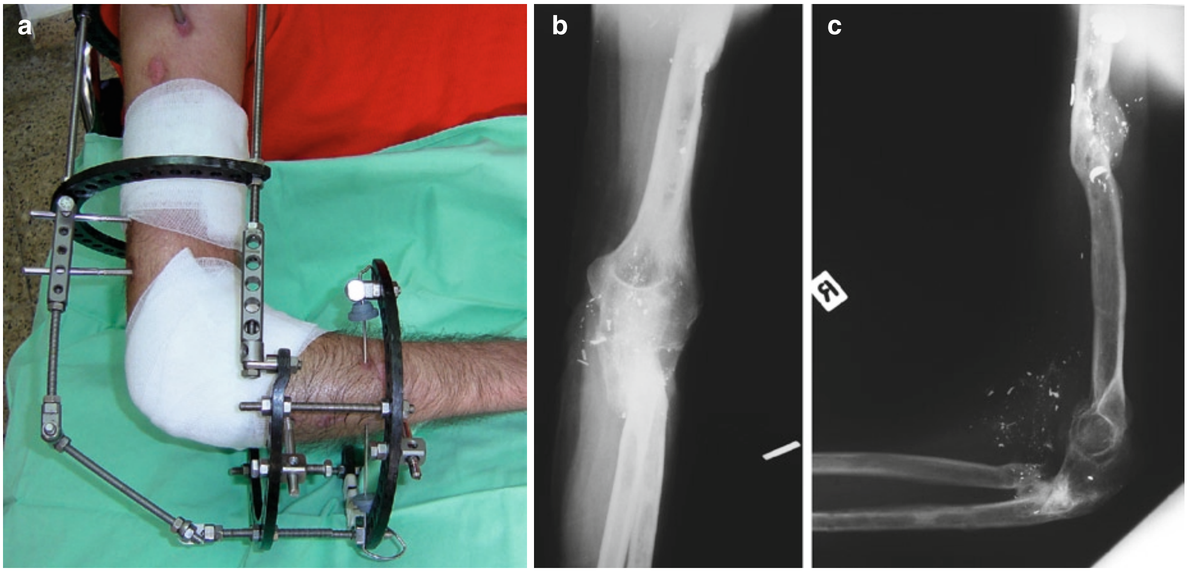


Fig. 15.20 A 20-year-old male with open Gustilo–Andersen type IIIB fractures of right humeral shaft, right proximal ulnar and radial bones with severe bone comminuting, and bone and soft tissue loss due to gunshot injury. Circular external stabilization of fractures and stable fixation of the elbow joint in a 90°elbow position for arthrodesis due to extensive tissue injury and loss, and neurological upper limb damage. (**a**) Clinical appearance of the trans-elbow fixation using Ilizarov external circular device. (**b**, **c**) Radiological pictures performed at a 2-year follow-up demonstrate solid elbow fusion at the 90° position

periosteal soft tissues and damaging the blood supply to the fracture site, reduces the local osteogenic potential, and often excludes the possibility of using the injury site for elongation and bone defect restoration. In the treatment of high-energy limb trauma, callotasis requires the presence of vascularized soft tissue coverage of the fracture site, contact between bone fragments, and only a small extent of bone tissue loss (up to 3 cm long). Metaphyseal localization of the callotasis site is preferred, owing to the greater vascularity of the metaphysic. The diminished vitality of the tissues in a zone of high-energy limb trauma greatly extends the period needed to achieve solid bone consolidation and, accordingly, prolongs the duration of fixation in the external frame. When the radiological appearance is that of a sparse bone regenerate, the rate of bone distraction must be decreased or temporarily stopped. An interim return to compression can be performed repeatedly ("accordion" maneuver) until a positive effect on bone induction is shown on the control radiographs (Fig. 15.21). Major reconstructions are better performed in relatively healthy tissue zones away from the focus of tissue damage.

15.5.7.2 Bone Reconstruction Using the Bifocal Technique

The absence of vascular tissue coverage of the fracture site, lack of contact between the bone fragments, loss of bone tissues (more than 2-3 cm), and diaphyseal localization of the fractures are the factors that deny regenerative tissue potential in the fracture zone and prevent distractional osteogenesis and solid fracture healing. Diaphyseal high-energy fractures of the lower extremities with extensive soft tissue and bone loss are the most common indication for utilizing the bifocal method of reconstruction.

The Ilizarov method is the most reliable way to restore bony continuity in a segmental defect and maintain equal limb length [23]. Bone regeneration is achieved by using osteotomy/corticotomy through a healthy area of bone in a zone of intact soft tissues, preferably metaphyseal in location, preserving the periosteum, and away from the zone of injury. The proximal metaphyseal location is the site of choice rather than the distal metaphysis because of its superior bone regeneration capacity [9]. The technique of osteotomy/corticotomy is of crucial importance, because the bone-healing process must occur in the osteotomy site. Therefore, it is necessary to use a "low-energy technique" of bone cutting (especially in high-energy trauma), which is minimally invasive and respects the vascular supply of the bone. A bone-cutting technique that damages the bone blood supply will delay or even prevent bone regeneration. Bone cutting using an oscillating or Gigli saw risks thermal damage. A percutaneous minimally invasive technique of subperiosteal bone cutting is chosen: only a small incision is required and bone viability is not compromised. The periosteum is incised longitudinally and elevated using a small periosteal elevator. Multiple, small 2 mm drill holes are made in the line of the planned bone cut and the cortices are severed using a small 5–8-mm osteotome. Now, careful rotation of the rings in opposite directions until a cracking sound is heard completes the procedure of the bone division (osteotomy–osteoclasis technique). After a 7–10-day latency period, the original length of the bone shaft is restored by gradually increasing the corticotomy gap, moving the intercalary segment away from the corticotomy site.

This technique permits the consolidation of the original fracture and also the elimination of the bone defect by the gradual controlled transfer of the mobilized intercalary bone fragment until it contacts and "docks" with the opposite bone fragment. Fixation in the external circular frame facilitates controlled gradual distraction in the zone of elongation, provides sufficient three-dimensional stability in the fracture zone, simultaneously eliminating deformities, and effectively compresses the fracture zone once the intercalary fragment has docked.

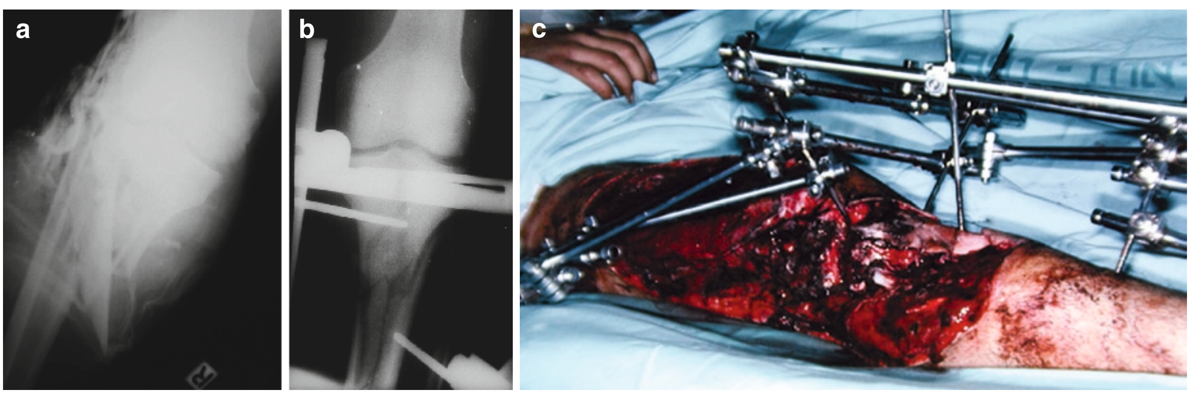


Fig. 15.21 A 19-year-old male with open Gustilo type IIIB left proximal tibial fracture with severe bone comminuting and massive soft tissue loss due to blast injury by antitank rocket. (**a**) Radiogram at the time of injury demonstrates severe comminuting of the proximal tibial bone. (**b**, **c**, **d**) Primary emergency care was carried out with debridement of soft tissues and stabilization of the fracture, including temporary knee bridging, using a tubular external fixation frame**.** Clinical and radiological appearance of the left lower limb after completing primary surgical debridement procedure. Note extensive skin and soft tissue loss over distal third of left thigh, knee joint, and proximal half of left leg. (**e**) Free tissue muscle latissimus dorsi flap and local muscle gastrocnemius flap were used to cover the exposed tibial bone and fracture site. The unilateral tubular trans-knee frame was exchanged at this stage for a circular tibial Ilizarov frame with freeing of the knee joint. Clinical appearance showed complete soft tissue coverage of the bone and fracture site. (**f**, **g**) Postoperative period was complicated by post-traumatic osteomyelitis of the tibial bone. Repeated serial debridement of the fracture site with sequestrectomies was performed. Local septic process and severe scarring in the fractures zone preclude bone graft procedure to replace the tibial bone defect. Repeated cycles of distraction-compression in the external fixation frame were used to stimulate bone regeneration process. Five centimeters of bone regeneration was achieved. X-rays demonstrate signs of bone consolidation process during fixation in the Ilizarov frame. (**h**, **i**) X-ray pictures 6 months after removing the Ilizarov frame demonstrate bone healing in good alignment with solid bone regeneration. Total time for external tibial fixation in the long-term treatment of this complex patient was 48 months. The patient was fully ambulatory during most of the treatment time. (**j**, **k**, **l**, **m**) Clinical photos at a 6-year follow-up after the removal of the Ilizarov frame demonstrate good function of the right lower limb. No recurrence of the local septic process was noted

Fig. 15.21 (continued)

Fig. 15.21 (continued)

New bone forms within the distraction zone as a result of the tension–stress effect, the bone defect thereby being filled in without the need for bone grafting. Distraction forces applied to the bone also create tension in the surrounding soft tissues, specifically the skeletal muscles, and initiate the sequence of adaptive changes known as distraction histiogenesis. Gradual lengthening may trigger events leading to tissue formation: angiogenesis in the dermis due to tissue hypoxia, dermis formation after tissue expansion, and muscle hypertrophy or hyperplasia that occurs by the recruitment of satellite cells [25]. Contemporaneously with bone regeneration limb lengthening, muscle growth is stimulated through muscle cell proliferation and fusion with lengthened myofibers at the level of the myotendinous junction. The production of large numbers of myogenic cells incorporated into the existing muscle fibers enables skeletal muscles to adapt to the new dimensions during lengthening [22, 24].

This technique of reconstruction is preferred in the management of patients after high-energy shin fractures with severe tibial bone defects and intact fibular bone, when the length of the injured limb segment is preserved. Reliable holding of the transported bone segment in the accurately assembled circular frame directs its controlled passage during the bone transport procedure. A rail technique of navigation of the bone fragment with introduction of a wire or thin nail into the medullary canal (often utilized in elective reconstructions) is unnecessary and bears the hazards of possible reactivation of infection and its extension along the nail and bone segment.

A distraction rate of 1 mm/day (1/4 mm × 4 per day) is recommended. Restoration of extensive bone defects demands a long period of external fixation, including the period of distraction and maturation (approximately 1 month of distraction and external fixation time per 1 cm of elongation). To shorten the length of treatment, especially external fixation time, a bifocal elongation osteotomy/corticotomy procedure may be performed.

Soft tissues lying in the route of the movement of the intercalary bone fragment (so-called bone transport) may shrink (collapse inward), due to the absence of the inner underlying hard tissue mass, resulting in shrinking of the circumference of the soft tissue envelope. Under these circumstances, if bone transport is continued, the skin can become invaginated onto the upper end of the transported bone fragment. Then, continuing bone transport can lead to the pinching and atrophy of the indrawn skin between the bone fragments.

With the onset of the signs of this dangerous complication, the rate of bone fragment movement must be slowed or even stopped. Subcutaneous thin wires can be used to support the sagging tissues, or elevation of the sagging skin is done by the shifting local soft tissue flaps or excision of the infolded skin.

During the prolonged period needed in treating large bone defects, a dense fibrous scar may form near the target fragment, preventing intimate bone-to-bone contact and bone union (the “docking” problem). In these patients, excision of the dense fibrous tissues from the docking site is needed to allow bone contact. At the time of debridement of the open trauma wound, it is desirable to perform reshaping of the “kissing” contact surfaces of the bone ends which are to meet after transport later on, to improve their contact surfaces and to achieve better stability when compressive forces at the fracture site are applied during the final stage of “docking.” An optional cancellous autogenous bone graft can be added to improve bone contact and fill residual defects on the facing surfaces of the bone ends. Bone grafting can be done only when signs of local infection are absent. Using the bifocal technique, extensive bone loss can be restored without the need for massive bone grafting.

A special technique is needed for open fractures with partial circumferential bone loss. Some bone remains (usually the posterior cortical area of the tibial bone) which is insufficient for bone stability due to its small bulk, even after bone union occurs. Moreover, such fragile fragments do not permit closure of the bone gap between the main bone ends necessary for strong bone healing. Damaged or absent local soft tissues that have suffered high-energy trauma preclude the use of an open bone graft. The gradual transfer of the bone fragment most connected to intact soft tissues shaped to the frontal aspect of the bone defect solves this difficult problem. The bone fragment to be transported is detached from the frontal end of one of the main bone fragments (partial corticotomy with bone transport).

Ring external fixation has the added benefit of immediate weight-bearing in the presence of extensive bone loss [13].

15.5.8 *Acute Temporary Malalignment in Limb Salvage*

15.5.8.1 Acute Limb Shortening

Open fractures do not heal without good coverage of the fractured area by well-vascularized soft tissue. Many complications are avoided if this step is completed early. The use of local and distant tissue flaps is not recommended due to the unavailability of viable local soft tissue or poor local healing potential due to a compromised vascular supply (single vessel limb, conditions after revascularization procedures) [8]. Revision flap coverage may not be an option after previous flap necrosis, and amputation remains the standard option for such patients [32]. For patients in whom high-energy limb trauma has caused open fractures and extensive soft tissue and bone loss, temporary limb shrinking using the Ilizarov external fixation device is an option to salvage the limb. Shortening of the severely injured limb is used to close an extensive soft tissue defect. Acute limb shortening followed by re-lengthening is a powerful technique for bridging soft tissue and bone defects and restoring limb function utilizing one continuous staged procedure [4].

Immediate soft tissue coverage achieved by acute shortening avoids the need for and morbidity of local or distant tissue flaps and free tissue transfers. Acute shortening with subsequent progressive lengthening of the bone is an accepted alternative for patients with an absolute or relative contraindication for free and local flaps, allows dealing with large soft tissue and bone defects, and eliminates dead spaces at sites of tissue loss.

Ample redundant soft tissue provided by acute shortening is used to cover exposed bone fragments and fracture area. After acute shortening, the need for free flap reconstruction is rare; most defects are closed primarily or by simple small local flaps or split skin grafts. Moreover, acute shortening in patients suffering from open fractures with vascular injuries (Gustilo type IIIC fractures) eliminates the need for blood vessel grafting by making end-to-end vascular suture possible, even overcoming the increased gap created by debridement of the ends of the injured vessels.

Temporary shortening of the severely injured limb after extensive radical debridement allows preserving of the potential for structural and functional restoration by guided graduated distraction with the Ilizarov method. The technique allows restoration of relatively large bone defects without the need for bone grafts and complicated local or free flaps, avoiding morbidity of donor sites and other serious complications. Additionally, the mechanical quality of the distracted bone is superior to cancellous bone grafts [38]. Lack of a donor site, morbidity, decreased operating time (important for patients with multiple organ trauma), good handling of both soft tissue and bone defects, and low complication rates are the main advantages of acute shortening for complex limb injuries [23, 31, 33]. Bone defects and soft tissue loss are handled simultaneously.

For a transversely oriented soft tissue defect, acute shortening produces adequate contact of the wound edges. In contrast, limb shortening for a longitudinally oriented wound can result in divergence of the wound edges, thereby creating a dilemma with regard to closing the soft tissue defect. An S-shaped extension of the wound solves this predicament. This simple maneuver permits the closure of the wound by the counter transfer of the conforming skin-fascia flaps (Figs. 15.22 and 15.23).

In acute shortening, progressive lengthening using the Ilizarov device is based on the same principle of tension stress that allows bone regeneration. The lengthening phase can be started only after complete soft tissue healing (usually after 2–3 weeks). The gradual distraction rate provides acceptable cosmetic results, and the bone length is restored during axial distraction (when the bone edges were well approximated and aligned at the acute shortening procedure). The restricted length that can be gained in the presence of extensive soft tissue trauma, caused by a high-energy injury, limits this callotasis technique. An additional metaphyseal corticotomy/osteotomy is indicated. Two-level elongation corticotomy of the proximal and distal bone fragments is indicated for patients having extensive bone defects. This procedure improves the structural quality of the regenerated bone, while the elongation and fixation time is shortened.

Acute shortening of the upper limb is well tolerated by patients. The upper extremity is a non-weight-bearing organ, thus it accepts shortening better while retaining more function as compared to the lower limb during the drawn-out lengthening procedure (Figs. 15.24 and 15.25).

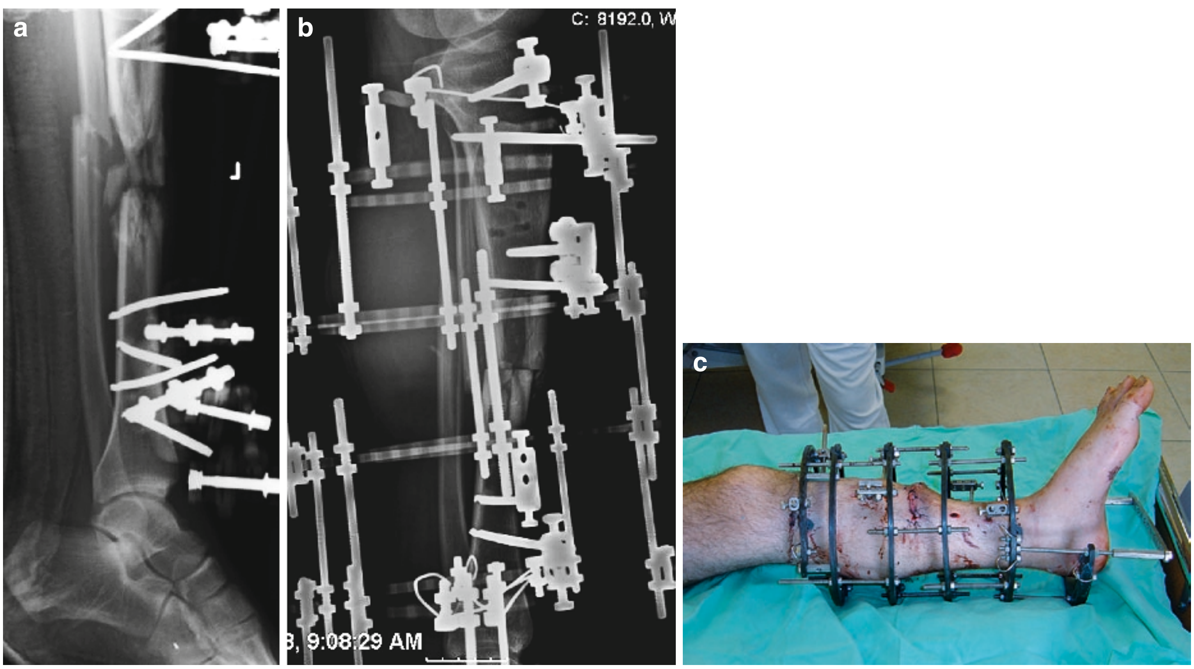


Fig. 15.22 A 23-year-old male with open Gustilo–Andersen type IIIB tibial fracture with bone and soft tissue loss secondary to blast injury. Acute shortening procedure was performed after radical wound debridement with the removal of free bone fragments and bone ends resection. (**a**) Primary stabilization of tibial fracture using tubular external fixator is performed. (**b**) Radiological picture demonstrates good bone ends contact after acute limb shortening and conversion to circular Ilizarov frame. (**c**) Clinical picture of the leg demonstrates adequate closure of transversely oriented soft tissue defect after performing acute shortening procedure. Note metal “horseshoe” attachment to the frame used for temporary compensation of the lower limb-length discrepancy and performing early weight-bearing on the injured limb

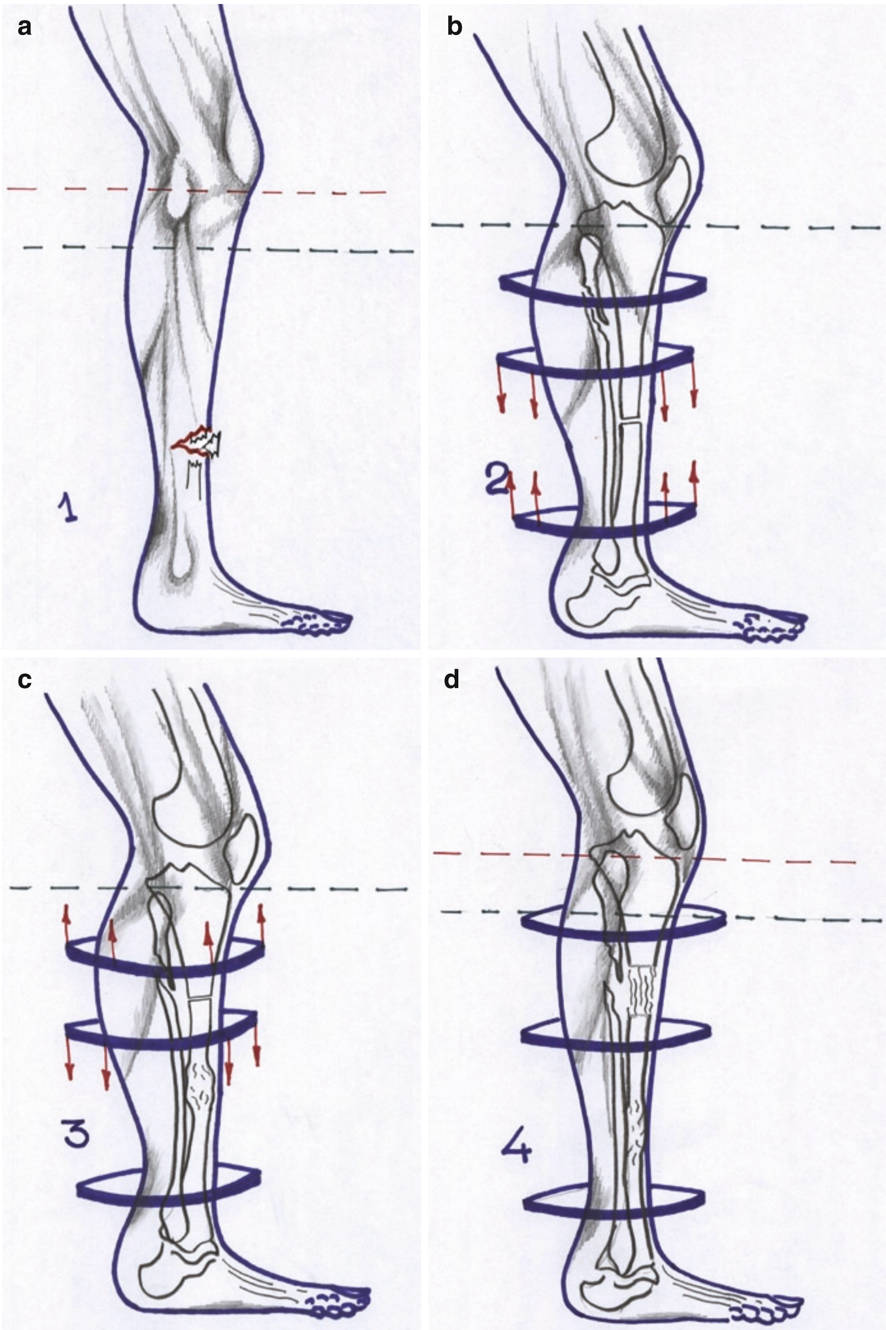


Fig. 15.23 Schematic representation of technique of temporary acute shortening. (**a**) Presentation of the limb on admission – open fracture with bone and soft tissue loss. (**b**) Debridement with acute shortening and stabilization in the external circular frame. (**c**) Proximal elongation tibial osteotomy is performed. (**d**) Limb length is restored by bone regeneration in the osteotomy site

Fig. 15.24 A 26-year-old male with open Gustilo–Andersen type IIIC tibial fracture with bone and soft tissue loss secondary to blast injury. (**a**) Clinical picture on admission (6 h after injury). (**b**) X-ray on admission demonstrates a comminuted fracture of tibial and fibular bones with bone loss. (**c**) Clinical appearance of leg in the operating theater after thorough washing of the wound using antiseptic solutions and soap. (**d**) Distal limb perfusion is restored using temporary intraluminal vascular bypass shunt to the tibialis anterior artery. (**e**) Intraoperative radiological picture at the stage of bone debridement. (**f**) Primary stabilization of tibial fracture with tubular external fixator is performed with temporary limb shortening. This procedure allows performing final vascular reconstruction by the end-to-end suture. (**g**) Clinical picture 3 days later: wound coverage using skin grafting was performed. (**h**) Clinical picture 2 weeks later demonstrates good skin graft healing. (**i**) At this stage, conversion to Ilizarov circular frame was performed. (**j**) Radiological picture after conversion to Ilizarov frame demonstrates contact between proximal and distal bone fragments. (**k**) Radiological photo performed 1 month after proximal elongation tibial corticotomy. (**l**) Radiological picture performed 8 months after proximal corticotomy shows good bone regeneration at site of elongation. (**m**, **n**) Radiological photos after completing reconstruction procedure. Tibial fracture is healed, 12-cm elongation is achieved, and leg length is restored. Total time in external tibial fixation: 18 months. (**o, p, q**) Clinical photo at follow-up one year after removal of Ilizarov frame demonstrates limb-length restoration and good ROM of knee and ankle joints

Fig. 15.24 (continued)

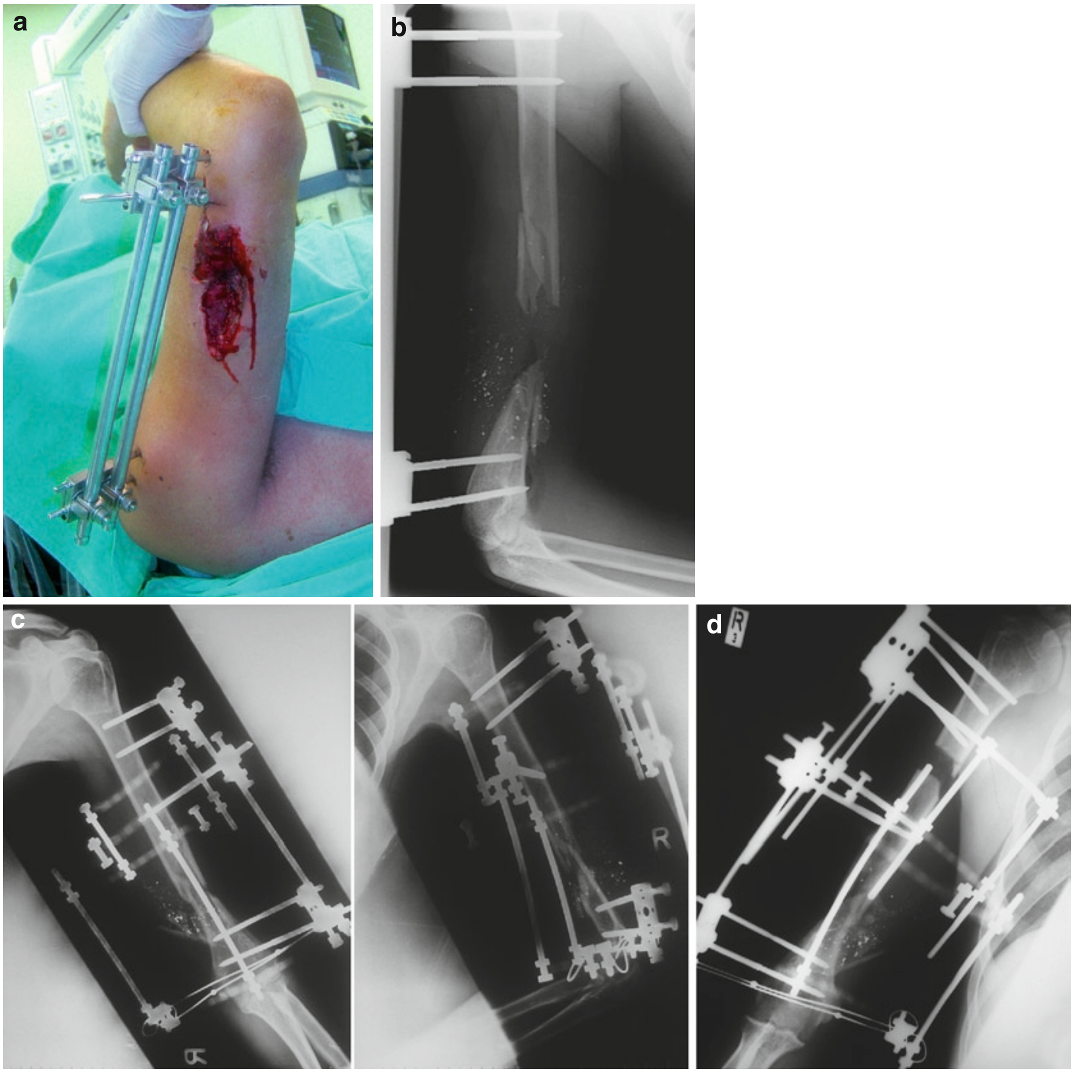


Fig. 15.25 A 23-year-old male with open right humeral fracture Gustilo-Andersen type IIIB with bone and soft tissue loss resulting from blast injury by antitank rocket. (**a**) Clinical appearance of right arm after primary debridement and skeletal stabilization using tubular unilateral external fixation frame. (**b**) Control postoperative x-ray of the right arm demonstrates severe bone loss, multiple small metal foreign bodies at facture zone. (**c**) After repeated debridement procedure, acute shortening was performed to diminish soft tissue defect. Control radiogram demonstrates contact between proximal and distal bone fragments fixed in Ilizarov external fixation frame. (**d**) Three weeks later, after healing of soft tissue wound, proximal humeral corticotomy was performed to eliminate distal bone defect using distraction osteogenesis technique. X-ray taken 1 month after corticotomy demonstrates humeral bone elongation. (**e, f**) Clinical pictures demonstrate active mobilization of right upper limb during external fixation in Ilizarov frame. (**g**, **h**) Ilizarov frame removed after 6 months of external fixation. Radiological appearance of humeral bone at 1-year follow-up demonstrates solid fracture healing and restoration of humeral bone length

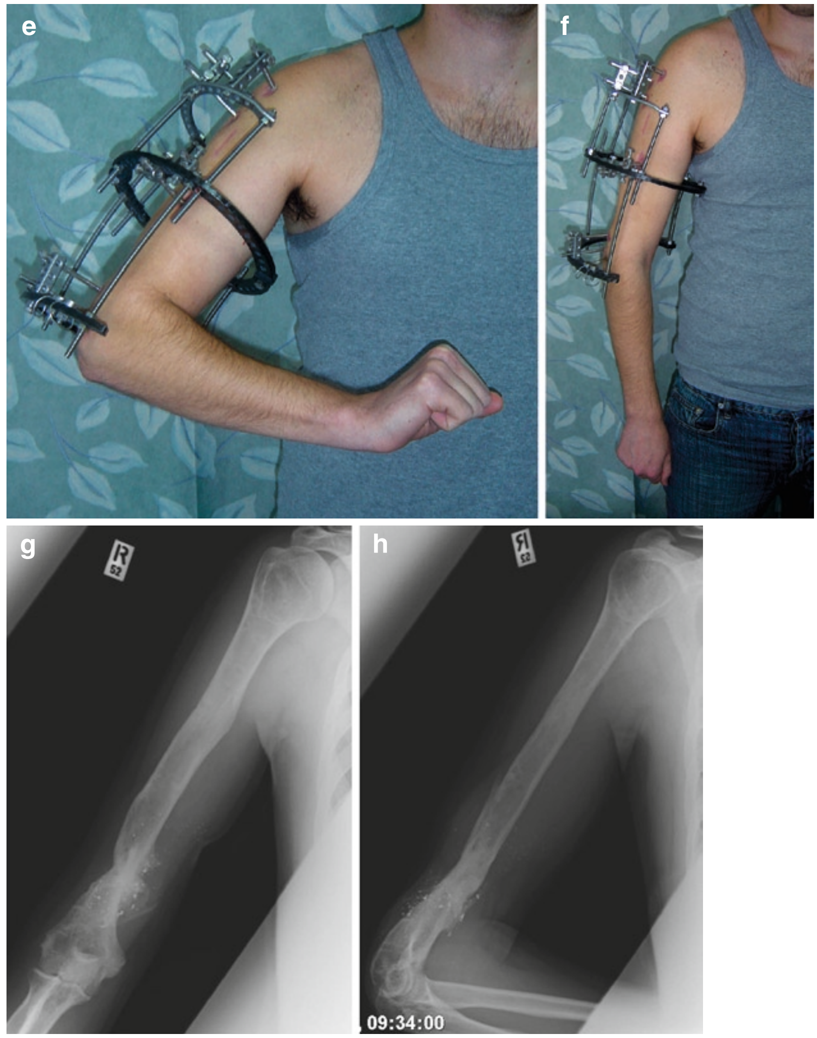


Fig. 15.25 (continued)

15.5.9 Acute Shortening and Angulation

In a patient with combined bone and soft tissue defects, it is mandatory to achieve skeletal stabilization and to cover the exposed bone as soon as possible, preferably during the initial care. In casualties who suffer from a one-side-located extensive soft tissue defect, the fracture site bone remains uncovered, even after performing acute shortening. Additional bone shortening is often unacceptable. On the other hand, residual bone exposure indicates the need for soft tissue reconstruction by a free flap as the only remaining alternative. However, acute shortening combined with angulation directed to the side of the main soft tissue loss to cover the exposed bone is the treatment choice to eliminate the soft tissue defect [8]. Primary closure of the soft tissue defect can be achieved without tension on the edges of the wound. The need to further shorten the bone or the use of complicated soft tissue reconstructive procedures can be avoided. The presence of post-traumatic vessels disease [15], an entity described after trauma including changes in the vascular wall and the perivascular tissue, the bad general condition of the patient and the absence of microsurgical skills reduce the chance of success of a free flap. The peripheral pulses, color, and capillary refilling must be checked at this stage to make sure that the angulation does not cause any vascular compromise. The acute angulation must be abandoned if signs of vascular compromise of the

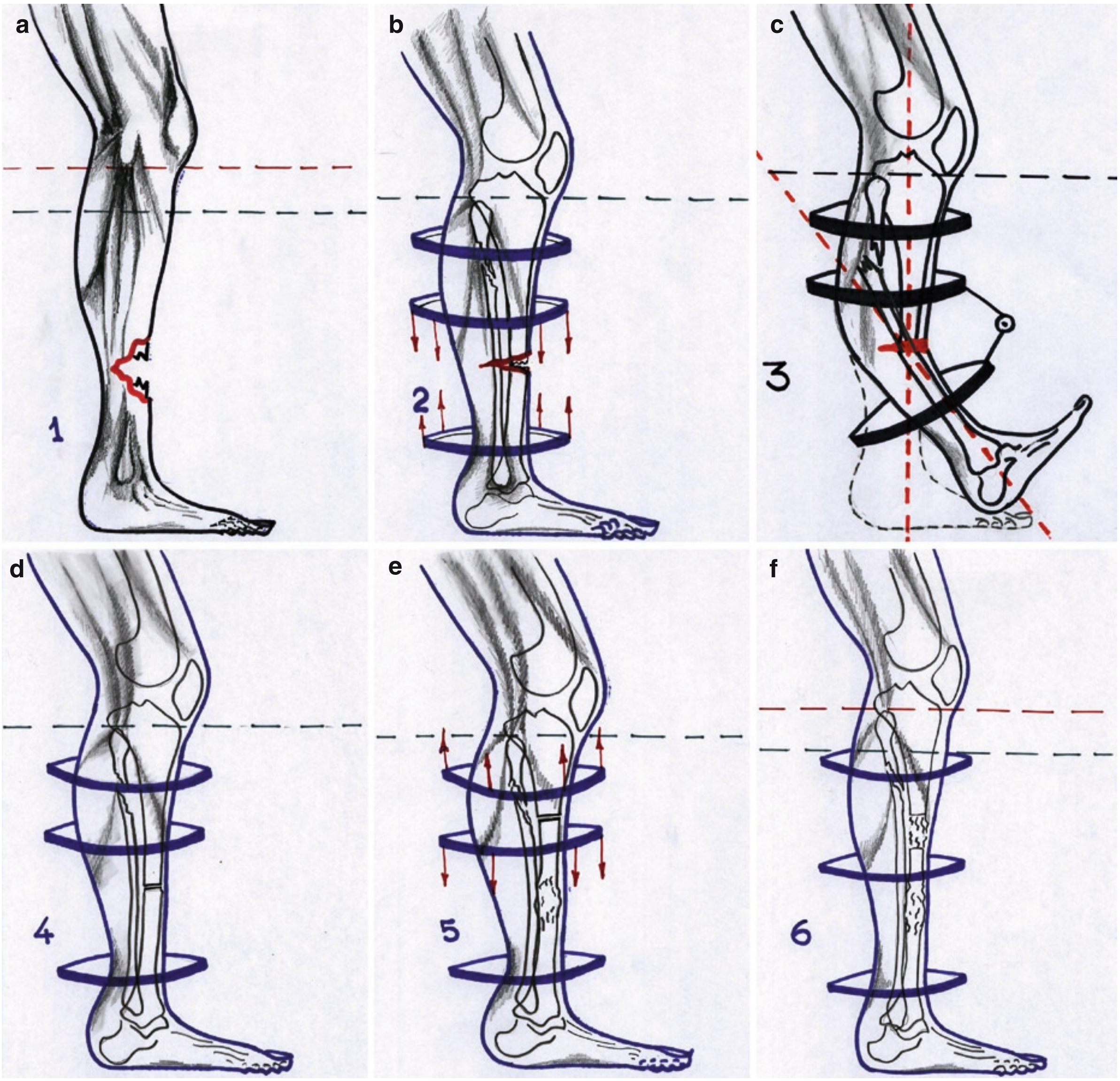


Fig. 15.26 Schematic representation of technique of temporary acute shortening and angulation. (**a**) Presentation of the limb on admission – open fracture with bone and soft tissue loss. (**b**) Debridement with acute shortening and stabilization in the external circular frame. Note uncovered fracture site after performing shortening procedure. (**c**) Acute angulation is performed to diminish soft tissue wound and coverage of the fracture site. (**d**) The leg is gradually realigned using Ilizarov frame. (**e**) Proximal elongation tibial steotomy is performed. (**f**) Limb length is restorated by bone regeneration in the osteotomy site

limb periphery appear. For this reason we perform this procedure without draping the foot or the hand. The angulated bone fragments are fixed using a hinged Ilizarov fixation frame. The hinges above the angulation site must be locked (Fig. 15.26).

Gradual progressive correction of the angulation can be initiated only when the wound is completely closed, usually after 3–4 weeks. The Ilizarov external fixator gains soft tissue length by stretching the skin and the scars, resulting in a good soft tissue envelope at the end of bone distraction. The pace of correction depends on the scar and soft tissue condition. *Haste must be avoided!* When realignment is achieved, an elongation corticotomy can be performed (proximally or distally,

Fig. 15.27 A 59-year-old male with open comminuted distal tibial fracture Gustilo–Andersen type IIIB with soft tissue loss on anterior aspect of the leg due to road traffic accident. (**a**) Admission x-ray. (**b**) Repeated surgical debridement with necrectomy and removal of free bone fragments were performed. To minimize the bone debridement and the soft tissue defect and to compact the bone edges, acute shortening (6 cm) and additional anterior 40° angulation at the fracture site was completed. The angulated bone fragments were secured with hinged Ilizarov frame (clinical photo). (**c**) Clinical photo demonstrates transversely oriented wound that closed without significant soft tissue deformity. Three weeks later, after healing of the wounds on the anterior aspects of the legs, gradual correction of misalignment was started. The axial alignment was restored over a period of about 3 weeks, by performing isolated anterior distraction of the hinged external fixation frame (x-ray). Leg length restoration was rejected by patient. (**d**) Radiological photos at a 6-year follow-up demonstrate radiological signs of consolidation. (**e**, **f**, **g**) Clinical views at a 6-year follow-up demonstrate active motions at the ankle joint. Orthopedic shoe with 5-cm elevation to left leg used by patient

according to local tissue conditions and localization of the longest bone fragment). In patients with large bone defects, a second corticotomy can be performed to increase the rate of lengthening. Full weight-bearing is promoted in the early postsurgical period by attaching an additional foot ring or plate to the external fixation frame, correcting the temporary shortening created. Intensive daily physiotherapy for muscle strengthening and prevention of stiffness and joint contractures starts on the first postoperative day and must be continued during the entire fixation period (Fig. 15.27).

15.5.10 Acute Shortening, Angulation, and Malrotation

In some especially complex cases of severe high-energy trauma with combined bone and soft tissue loss, the bone fragments remain exposed and deprived of soft tissue coverage even after performing acute shortening and angulation. Consequently, an additional step to achieve a soft tissue covering for the bone is required. Supplementary rotational displacement of the ends of the injured segment can bring about a decrease of the wound size, and approximate the edges. The temporary gross deformity created supplies enough soft tissue to cover the bones and bring about rapid autogenous wound closure without the need for any grafting procedures [35, 41]. A multiplicity of repeat debridements is avoided, since the initial debridements can be as radical as necessary in the sure knowledge that the wound can be closed. Once healing is well established and infection has been avoided, the deformity can be gradually secondarily corrected and limb axis and length restored.

The fixed limb segment is usually eccentrically situated in the circular fixation frame, and the bone itself is also eccentrically located within the limb segment. The center of rotation of the frame is always placed exactly in the center of the ring. Thus, performing rotation in the circular frame, a bone fragment attached to the ring in an eccentric position (outside the center of rotation) can result in lateral displacement with regard to the facing bone fragment, fixed onto the opposite side of the external fixation frame. The greater the malrotation, the more asymmetric is the position occupied by the bone fragments in the rings, and the greater the lateral translation of the fragments in the final stage of the derotation procedure. By attaching additional connection plates to the rings at the point nearest to the bone, the external configuration of the frame is changed. In this way, the bone is placed in the central position of the modified external frame and also in the

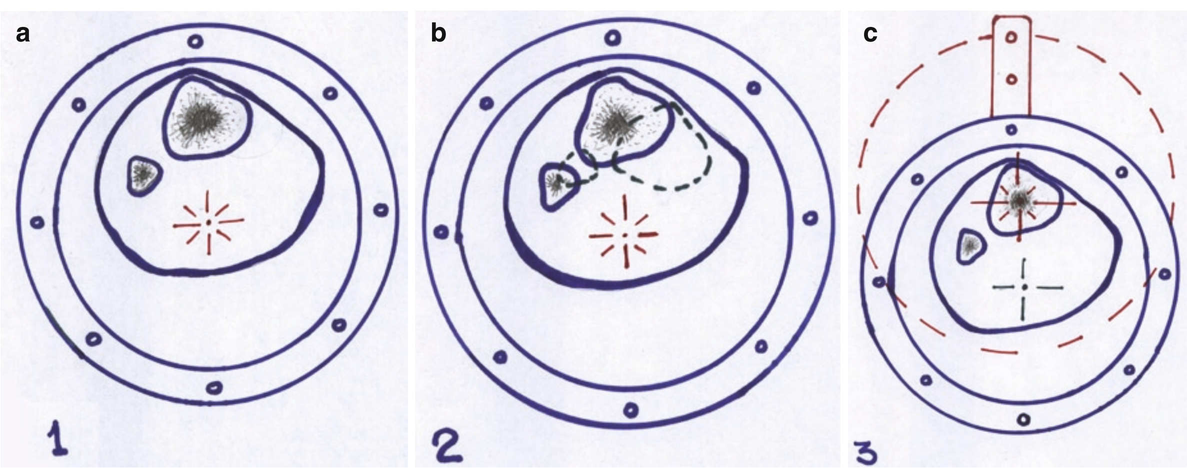


Fig. 15.28 Schematic plane of the derotation process in the circular fixation frame. (**a**) Note eccentric position of fixed segment of the limb and also bone fragments in the circular fixation frame. Rotation center of the frame in performing the rotation motion placed in the center of the ring. (**b**) Lateral displacement of the eccentrically placed bone fragment due to rotation in the circular frame. (**c**) Attachment of additional connection plates to the rings helps to change external configuration of the frame. Resulting from this procedure, the bone fragments are placed in the central position of the modified external fixation frame, also the center of the rotation motion

center of followed rotation (the bone is now in the center of a new virtual ring). Thus, during the process of derotation, the bone will retain its central position, and lateral displacement of the moved bone fragment can be avoided (Fig. 15.28).

Continuing the treatment of this complex patient, gradual derotation of the limb in the Ilizarov frame was performed later, together with distraction of the bone regenerate and full limb-length restoration. The derotation process can be combined in time with the process of elongation in the frame, which can significantly shorten the general duration of external fixation time and, accordingly, the general treatment time (Fig. 15.29).

Similar maneuvers to establish and later reverse a combination of malalignments can be performed in a Taylor Special Frame [27, 30].

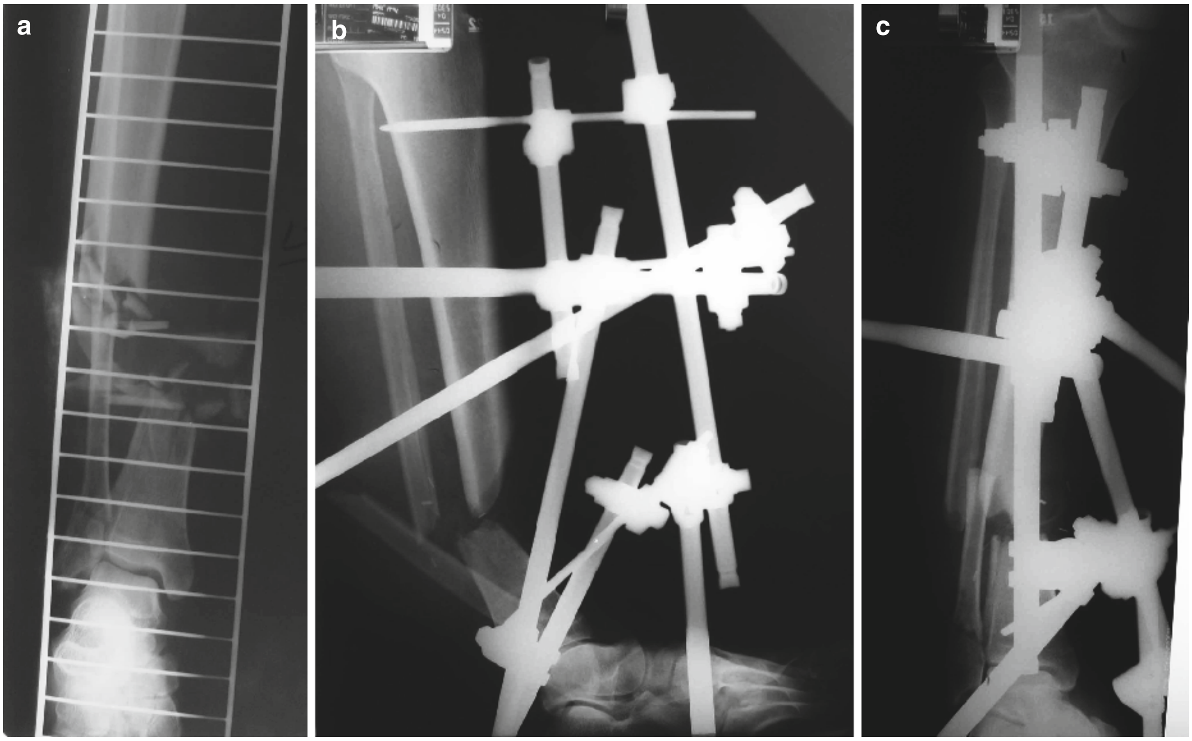


Fig. 15.29 A 49-year-old male who suffered from open Gustilo type IIIC left distal tibial fracture with severe tissue and bone loss due to road traffic accident. Lesion of tibialis anterior and posterior arteries was found on exploration of the wound. (**a**) Admission x-ray of both lower limbs. (**b**, **c**) Primary emergency care was carried out with debridement of soft tissues, repairing tibialis anterior and posterior arteries, and stabilizing the fracture with a tubular external fixator. Fixation of bone fragments was performed with anteromedial angulation due to severe soft tissue loss on the anteromedial side of the tibial bone and fracture site. (**d**, **e**) Even after performing anteromedial angulation, the fracture site remains uncovered with 7×3 cm soft tissue defect. (**f**, **g**) Angiography performed in planning of definitive reconstructive procedure shows occlusion of repaired tibialis anterior artery. (**h**) Assembly of circular Ilizarov external fixator was performed, preserving position of bone fragments achieved by the primary fixation procedure. (Note fixation of cantilevered half-pins of the primary tubular fixator to the rings of the Ilizarov frame.) Thus, the site of vascular anastomosis of the single remaining repaired tibialis posterior artery was undisturbed. (**i**, **j**, **k**, **l**) Additional malrotation of foot and distal tibial fragment resulted in significant decrease of wound width, bringing its edges together. Radiological and clinical views of the malaligned limb included acute shortening, angulation, and malrotation. The angulated bone fragments are secured with a hinged Ilizarov frame, including foot attachment. (**m**, **n**, **o**, **p**) Four weeks after angulation procedure, the wound was completely closed and progressive correction of the angulation was initiated. Three weeks later, the angular malalignment was gradually restored (clinical and radiological views) and compression of the tibial bone fragments was performed. (**q**, **r**) Radiological photos performed 2 months after proximal elongation tibial corticotomy show good bone regeneration. (**s**, **t**, **u**) Note: Attachment of additional connection plates to the ring changes external configuration of the frame. Thus, during derotation process, bone retains its central position, and lateral displacement can be avoided. (**v**) Full weight-bearing on fixed Ilizarov frame leg at early stage of derotation procedure. (**w**, **x**, **y**, **z**) Clinical and radiological photos after completing the reconstruction procedure. A 12-cm elongation is achieved and leg length is restored. Total time in external tibial fixation: 13 months. (**z1**, **z2**, **z3**, **z4**, **z5**) Clinical and radiological photos at follow-up half -year after removal of Ilizarov frame. Radiological photos demonstrate bone consolidation of distal tibial fracture, with solid bone regeneration after completing 12-cm proximal tibial elongation

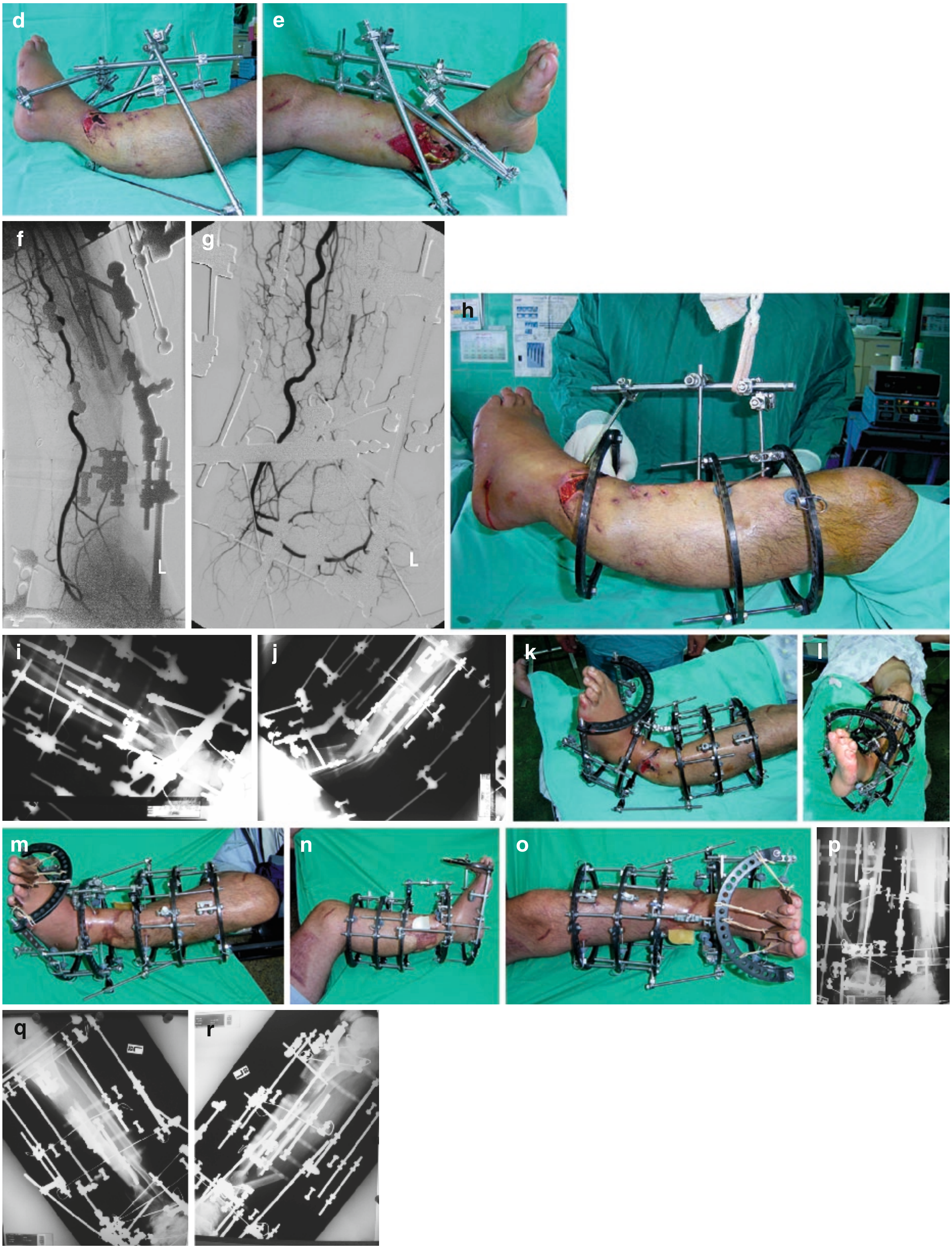


Fig. 15.29 (continued)

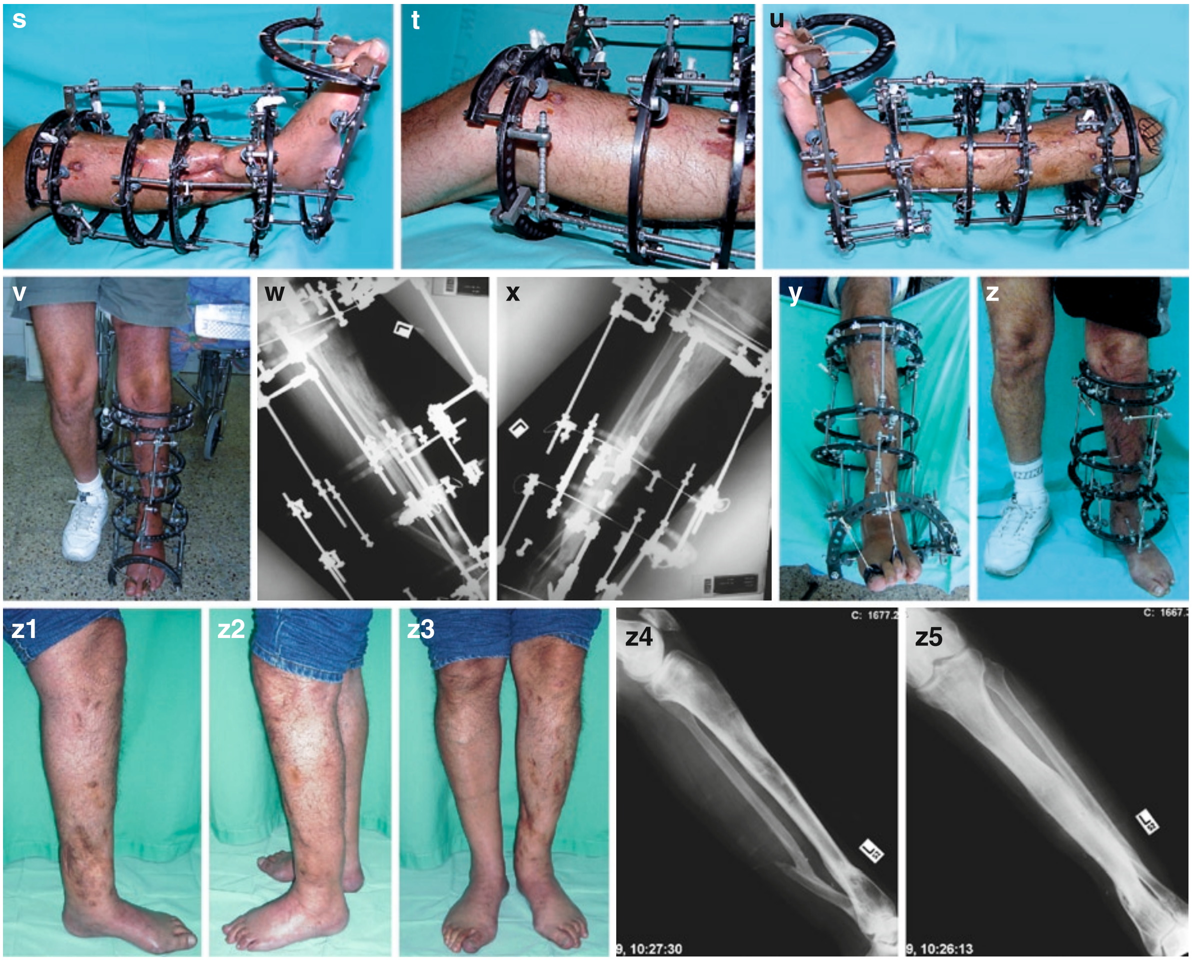


Fig. 15.29 (continued)

15.6 Summary

Generally, primary temporary acute malalignment by shortening and angulation ("shrinkage") of the critically injured limb segment while stabilized in an external fixation frame allows the use of the remaining vital soft tissues to cover wounds in severe limb injuries with massive combined bone and soft tissue loss, avoiding the risks of traumatic complex tissue transplantations, and facilitating vital blood vessel and nerve repair. Large wounds with exposed bone heal rapidly by the apposition of healthy soft tissues. Limb axis correction and tissue induction or reconstruction are then achieved by gradual realignment and distraction through one or more osteotomies/corticotomies using Ilizarov's callotasis bone induction technique and controlled by circular or hybrid frame external fixation constructs [18]. Stable three-dimensional bone stabilization in the circular fixation frame allows early functional weight-bearing even in such complex patients. Following frame placement, the patients should be encouraged to walk as soon as tolerable with full weight-bearing.

Returning to the axiom that the condition of the soft tissues is the determining factor in treating patients suffering from high-energy trauma, we emphasize that fixation of the injured limb in the circular frame establishes optimal conditions for the soft tissues in the early definitive phases of the treatment process. Circular frames enable continuous elevation of the injured segment and afford all-round mechanical protection, shielding the limb evenly on all sides from pressure and avoiding gravitational impingement on the skin and soft tissues on the inferior surface of the limb. Moreover, by using this method, it may be unnecessary to apply circular pressure bandages to the injured limb segment with possible distal limb edema. Local pressure on the wound, if needed, can be achieved by placing a pressure cotton pad between the wound and the corresponding ring of the frame, eliminating undesirable pressure on other areas near the injured segment. Fixation in the circular frames can be a useful method of treating complex injuries such as burn trauma, especially circular burns, compartment syndrome, and post-fasciotomy conditions.

Proper fixation of the frame components is essential: all wires, bolts, nuts, and rods should be securely fastened. Thus, additional inspection of the assembled fixation frame must be performed in the final stage of the operative procedure, checking the degree of its stability and also the stability of the fracture fixation. Skin and soft tissue tension around fixation elements are checked and eliminated. Unreleased skin tension may cause severe postoperative pain and joint stiffness, and can lead to local skin necrosis and pin-tract infection.

15.7 Conclusion

A staged protocol of external fixation, including primary temporary unilateral tubular stabilization followed by definitive circular Ilizarov/Taylor/hybrid fixation and reconstruction by the use of customized frames, is an effective method for the treatment of patients with severe damage to the limbs caused by high-energy war injuries.

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