Open Fractures

14

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Generally, the principles underlying the treatment of patients with open fractures involving the limbs are similar to those discussed in Chaps. 2, 3, and 7. Therefore, in this chapter we consider only the most important, fundamental aspects of external fixation in the management of open limb fractures.

The assemblies of the external fixation devices comprise only the basic frames, as was the case for the fixation frames described in Chaps. 10, 11, 12, and 13. Nevertheless, it must be kept in mind that detailed, precise, and careful preoperative planning together with optimal external fixation frame configurations is the keystone of successful treatment. The number of constructional elements, their localization according to the fixed bone fragments, and the general assembly of the frame should meet the specific needs of the patient and his or her clinical situation. The injured limb should not be condemned to the "Procrustean bed" of the standard fixation frame!

14.1 Fixation Methods in the Treatment of Open Limb Fractures

The type of bone damage, even in patients suffering from severe bone comminution and/or bone loss, is not the most important factor in choosing the optimal treatment method. Rather, the condition of the soft tissues and the degree, depth, and extent of the damage are the basic defining factors that ultimately determine the long-term results and final outcome.

There are a number of criteria underlying the selection of the optimal external fixation technique for the treatment of complex open fractures, including those caused by gunshot wounds. Among them, the most important is the degree of skin damage according to the IO scale, the degree of muscle and tendon damage according to the MT scale, the degree of neurovascular damage according to the NV scale, and the extent of the bone damage (types A–C) according to the AO/ASIF classification [1] The degree of contamination and infection of the traumatic wound must also be determined. In addition, the Gustilo-Anderson index, based on the size of the wound and the amount of soft-tissue injury, is a very useful in dealing with open fractures [215, 216].

In open fractures with skin perforation from the inside (IO1) or a laceration of the arm, forearm, or thigh up to 3–5 cm in size (IO2) with limited damage to a single muscle group (MT2), and in the absence of neurovascular damage (NV1), the bone fragments usually need not be isolated during primary surgical treatment. These types of injuries correspond to IA–IB compound fractures according to the Kaplan-Markova classification [217] and Gustilo types 1 and 2. The bone fragments are repositioned and fixed as in simple fractures following drainage and suturing of the wound.

In the treatment of gunshot-induced fractures, primary surgical debridement of multiple point wounds that do not contain foreign bodies and are not accompanied by a growing hematoma or a disorder of the peripheral circulation is not indicated [218, 219]. However, a different approach is required: in skin wounds longer than 5 cm, if there are nonviable areas (IO3), if there is considerable contusion through the whole thickness of the skin, in graze wounds or if there are skin defects (IO4), if there is considerable damage to the muscles (MT3), if there are muscle defects or rupture of the tendons, or if there is extensive muscle contusion (MT4). These types of damage, according to the classification of Kaplan and Markova, correspond to compound fractures IIA, IIB, IIIA, and IIIB. In the Gustilo classification, these are type 3 fractures.

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Fig. 14.1 Severe complications due to irrational primary internal fixation in the treatment of open complex high-energy fractures. (**a**) Extensive skin and soft-tissue post-necrotic defects with an uncovered internal fixator after primary open reduction and internal fixation in the treatment of a blast injury to the right lower limb. (**b**) Skin necrosis with fixation-plate denudation after primary internal fixation of an open high-energy ulnar fracture with severe soft-tissue damage

Thus, internal fixation methods, including intramedullary nailing and plating, can be applied in the treatment of open low-energy limb fractures with relatively limited soft-tissue damage (Gustilo types 1 and 2). In the management of open limb fractures accompanied by severe and extensive soft-tissue damage (high-energy Gustilo 3 fractures), the preferred treatment approach is based on the sparing principles of minimally invasive methods of bone stabilization. However, the immediate reduction of open bone fragments and the surgical implantation of the internal fixation devices can lead to additional soft-tissue trauma, increasing the likelihood of wound healing problems and septic complications. Indeed, the implanted internal fixator can become a massive foreign body, supporting local septic processes. This is especially the case in the treatment of patients with significant soft-tissue loss and insufficient fracture site coverage (Fig. 14.1).

External fixation provides bone stabilization without the need for an additional surgical incision, thus avoiding soft-tissue trauma, bone stripping, and blood loss, and without the presence of massive additional foreign bodies (internal fixators) in the fracture zone. Thus, minimally invasive external fixation is an effective and preferred method in the initial treatment of open high-energy fractures characterized by extensive and complex soft-tissue damage.

14.2 Debridement and Primary Bone Fixation Using Unilateral External Fixation Frames

External fixation frames types I and II (Table 1.1) provide an effective method of fracture stabilization, permitting sufficiency control of the wound, vascular repair, and subsequent plastic-surgery coverage (Fig. 14.2).

Unilateral external fixation frames provide primary fracture stabilization either "in situ" (e.g., when the fracture is immediately stabilized without reduction in critical general condition of patient) or after re-alignment of the bone fragments during operative manipulation. This approach is largely analogous to the fixation method used in osteosynthesis.

In the acute trauma setting, unilateral external fixation provides a rapid, efficient, and relatively simple method of fracture stabilization, retaining the distance between bone fragments and preventing contracture of the muscles, thus allowing post-operative mobilization and facilitating patient discharge. The average time required to place a tubular external fixator is 20–30 min [220, 221]. In addition, early mobilization of the injured limb is possible, greatly simplifying the post-operative nursing care of the multiple-trauma patient (Fig. 14.3).

Bone fragment fixation achieved using external frames also allows primary fracture stabilization to the extent that the patient can be discharged from the hospital relatively soon after treatment, with early functional mobilization of adjacent unfixed joints. This modular and versatile treatment strategy may be employed for fractures of almost any configuration, severity, and location and in the presence of various skin and

Fig. 14.2 Unilateral external stabilization of an open femoral fracture demonstrating the possibility of an adequate surgical approach around the injured limb segment

Fig. 14.3 (**a**, **b**) Primary fracture stabilization using unilateral external fixation frames, allowing "damage control" in the treatment of patients with complex and multiple trauma

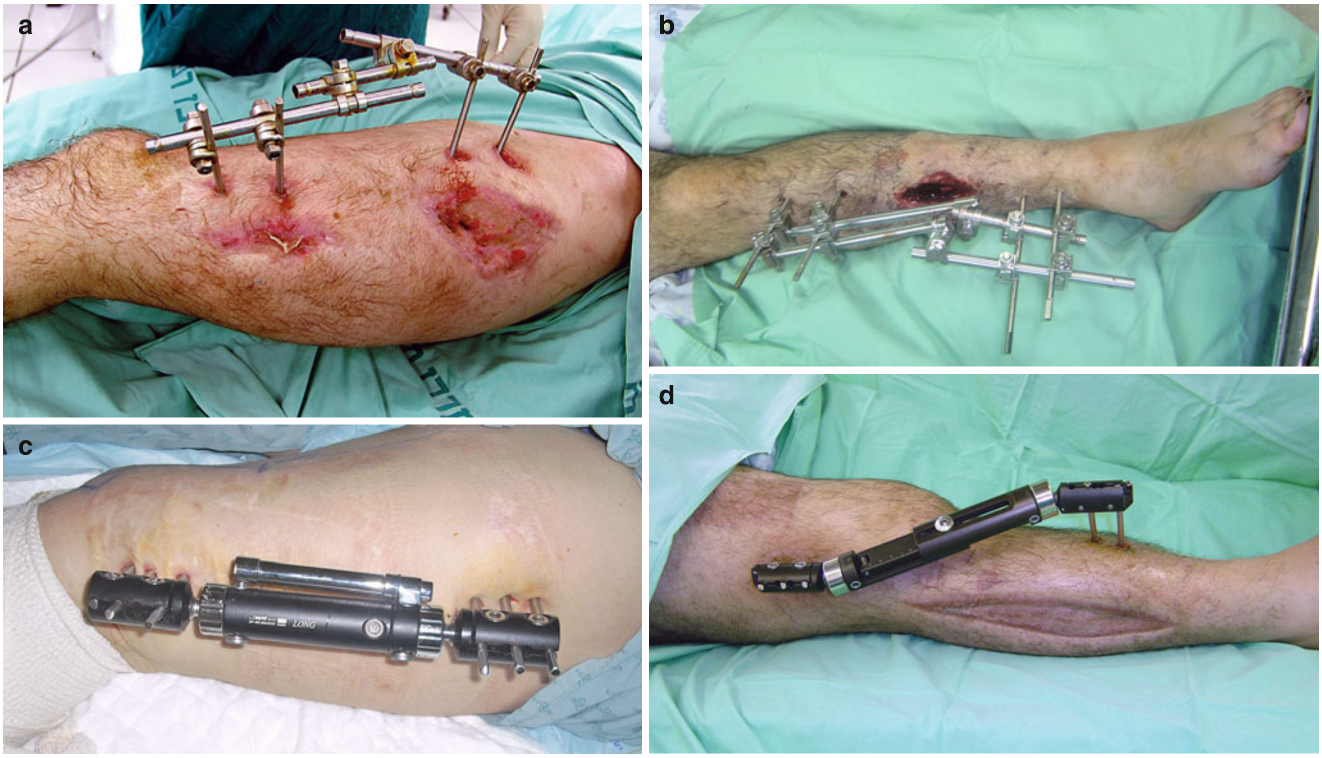


Fig. 14.4 External fracture fixation using the AO tubular external frames (**a**, **b**) and OrthoFix device (**c**, **d**)

soft-tissue conditions or even loss. The main difficulties and disadvantages associated with unilateral external fixation frames are discussed in Chap. 2.

Thus, the main indication for unilateral external fixation frames is open high-energy fractures with extensive and complex soft-tissue damage and loss (Gustilo 3 fractures). These multiple trauma patients, including those who are hemodynamically unstable and with complex pelvic fractures, require minimally invasive and rapid fracture stabilization. For such cases, many different tubular external fixation systems have been developed, such as the devices of AO, Hoffmann, Orthofix, Dinafix, and EBI-fixators (Fig. 14.4).

Our fixator of choice for primary stabilization of open limb fractures is the AO tubular external frame (Synthes AG, Chur, Switzerland), used in a single-plane unilateral configuration [222]. This is a rapid, modular, and simple method of stable primary fracture stabilization after severe complex trauma. A minimal number of basic frame components can be tailored to address specific surgical problems and anatomic sites. Figure 14.5 shows the basic frame components of the AO tubular external fixator (Synthes).

Copious, massive, repeated irrigation is an essential step in primary wound management during debridement. High-pressure pulsatile lavage (HPPL) may further damage the soft tissue by driving contaminants deeper into tissue already compromised by trauma, rather than removing them. This is especially likely in patients with high-energy gunshot wounds, blast injuries, and severe crush injuries.

The entrance and exit sites of the gunshot wound should be excised and widely dissected. Skin margins are excised as economically as possible. The wound canal and wound pockets are revised, with excision of all devitalized tissues. For patients with vascular injuries (Gustilo 3C fractures) or when crush damage to a limb is significant, prophylactic fasciotomy should be performed to prevent compartment syndrome. Connections between bone fragments and the surrounding soft tissue should be preserved. Denuded and comminuted bone fragments with questionable viability must be removed, avoiding devascularization of the fracture zone. Large free bone fragments can often be saved after their massive irrigation.

The presence of an open fracture and related wound does not prevent the extremity from the complication of compartment syndrome, as an open fracture does not automatically relieve the compartment of the injured limb. Consequently, even these patients can develop compartment syndrome. Thus, fasciotomy should be performed during the primary debridement procedure by longitudinal widening of the post-traumatic fascial defects.

Surgical gloves and all surgical tools must be changed after copious massive irrigation, primary radical debridement of the wound, and the removal of foreign bodies are completed. The injured limb is re-prepared with antiseptics and re-draped according to basic surgical rules. It is desirable to leave the distal parts of the injured limb exposed for ongoing visual inspection of the fingers or toes, including color, capillary filling, palpation of peripheral pulses, and instrumental control of peripheral perfusion and oxygenation.

The non-standard conditions posed by severe and complex injuries frequently necessitate significant expansion of the surgical access anywhere along the limb. Moreover, the introduction of additional external fixation elements away from the zone of injury may be required. Thus, it must be possible to fully expose the operated limb, freeing it from the surgical drapes. The adjoining proximal and distal joints must be observed during surgery to avoid unintentional malpositioning (usually malrotation) of the bone fragments during the bone fixation procedure.

Prior to the half-pin insertion procedure, all potentially dangerous zones, including the locations of the major vessels, nerves, and musculo-tendinous units, as well as large bone fragments and pertinent skeletal landmarks, should be

Fig. 14.5 Basic frame components of the AO tubular external fixator (Synthes): (**a**) threaded Schanz screws (5-mm diameter); (**b**) stainless steel tubes; (**c**) adjustable clamps tube-to-Schanz; (**d**) adjustable clamps tube-to-tube

Fig. 14.5 (continued) (**e**) triple trocar: trocar 3.5 mm, drill sleeve 3.5 mm, drill sleeve 5.0 mm, and drill bits; (**f**) universal chuck with T handle, socket wrench, and combination wrench (11 mm)

marked on the skin using a marker pen. The potential for non-anatomic localization of important structures due to displacement of the bone ends and surrounding soft tissues must be kept in mind. A preoperative marking procedure can considerably facilitate the operation, reducing its duration and the probability of iatrogenic complications.

Considering the significant damage to the bone and soft tissues due to open high-energy trauma, the choice of levels and positions for the introduction of the fixation elements to the bone may be substantially limited. Therefore, except for the "reference positions" other localizations, with the exclusion only of zones containing the main neurovascular structures ("safe positions"), can be more widely used. Exceptionally, the temporary insertion of half-pins into the uncovered bone can be carried out. Then, after stabilization of the patient's general condition and improvement of the local soft-tissue status, these half-pins should be re-inserted at more suitable sites along the injured limb segment, i.e., the "recommended positions" (Sects. 14.3 and 14.4).

A thin Kirschner wire, used as a probe, is a helpful tool to determine the position of the displaced fragments and to identify the correct site and optimal direction for subsequent half-pin insertion into the bone.

In unilateral external fracture fixation, a pair of 5.0–6.0 mm threaded half-pins is introduced into each of the main bone fragments (proximal and distal) of the tibia, humerus, and forearm bones (Fig. 14.5a–c). In large and/or obese patients with oblique fracture configurations or in patients with severe comminution of the bone fragments, as well as in the stabilization of femoral shaft fractures, three or even more half-pins should be introduced into the proximal and distal main fragments (Fig. 14.6d). External fixation of femoral and tibial fractures is performed using 5–6 mm screws. In external fixation of the humerus 5 mm screws are used, and in the forearm, foot, and hand bones 3.5–2.7 mm screws.

Short femoral or tibial bone fragments should be fixed with three half-pins in order to avoid trans-articular bridging.

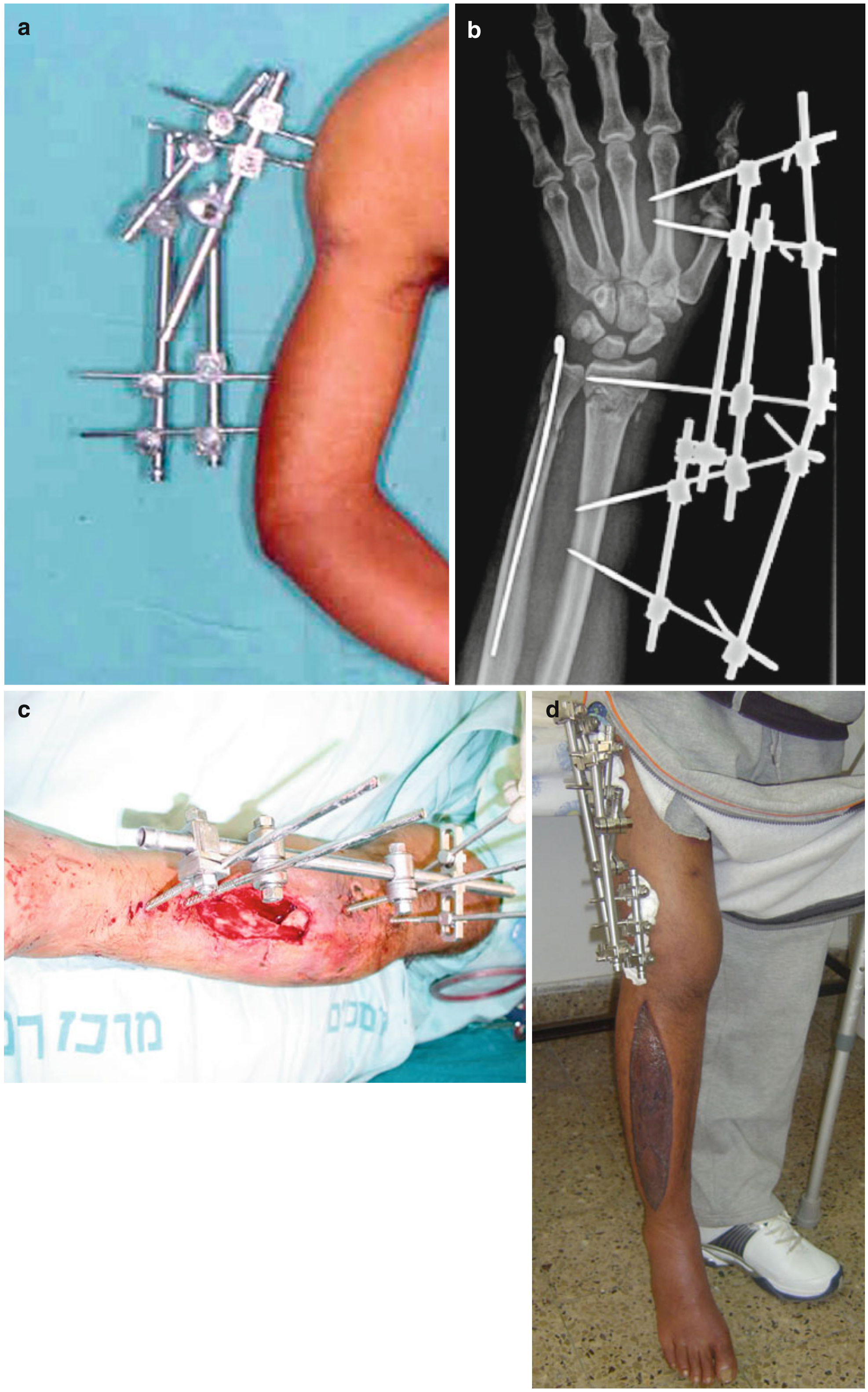


Fig. 14.6 External fixation of the humerus (**a**) and forearm bones (**b**) with introduction of a pair of screws into the proximal and distal bone fragments. In external fixation of the tibia (**c**) and femur (**d**), two or three screws are inserted into the proximal and distal bone fragments

In the fracture reduction procedure, the wide base of the external fixation frame is particularly stable—an additional benefit over a prolonged fixation period. Half-pins are inserted into the bone fragments close to the fracture zone at a distance of 4–5 cm from the ends of the main bone fragments. The most proximal and distal half-pins are introduced into the bone near the metaphyseal zone. The degree of stability can be increased by the non-parallel multi-scheduled introduction of bone-fixing elements (70–120° to the bone axis) (Figs. 2.24 and 2.25).

Fig. 14.7 External fixation of a tibial bone fracture

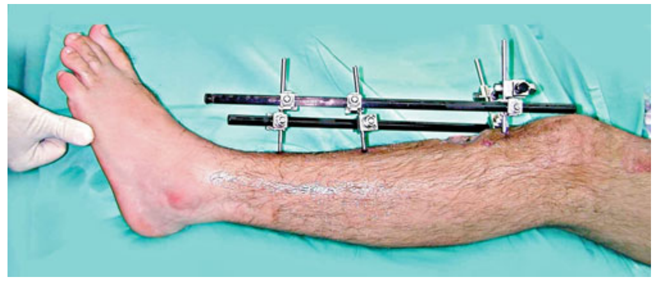


Fig. 14.8 External fixation of a tibial fracture using the AO tubular external fixation frame

Half-pins should be introduced into the bone using versatile projections of the different positions, for example, position 8 at level I and position 10 at level IV.

Reduction of the distance between a bone and a tube of the external fixation device also increases the stability of fracture fixation. During the fracture fixation procedure, all Schanz screws are usually inserted into the proximal and distal femoral bone fragments from the lateral side (positions 8, 9, 10). The approach for screws introduced into the tibial bone at each level is wider: positions 3–9 (anterior hemisphere of the segment), except for the contra-indicated positions at levels VI, VII, and VIII. For the stabilization of ulnar bone fractures, it is advisable to use between positions 5–9 in the insertion of the fixation screws. The insertion of half-pins into the humeral or radial bones due to complex anatomic features of these segments, must be performed according to the recommendations, given in Chap. 5.

The external ends of half-pins inserted into the proximal and distal bone fragments are fixed to the corresponding short longitudinal tubes using special tube-to-screw connectors. The tubes of each of these proximal and distal blocks are then connected using universal tube-to-tube clamps. Manual alignment and reduction are stabilized by tightening the clamps after clinical and radiological control of the fracture's reduction (Figs. 14.7 and 14.8).

Temporary trans-articular bridging of the injured limb is indicated in complex peri-articular and intra-articular fractures, extensive osteo-ligamentous injuries, or intra-articular penetrating injuries, and in the presence of severe damage to the capsule and ligamentary complex of adjoining joints. In addition, temporary trans-articular bridging fixation is an effective method to increase stability in patients with very short para-articular bone fragments. Technically, this type of trans-articular fixation can be achieved by inserting a pair of additional half-pins into the bone from the opposite side of the fixed joint. The external ends of these half-pins are fixed to each other and then to the primary external fixation frame using two longitudinal tubes, thereby increasing the stability of the fracture fixation itself (Fig. 14.9).

Temporary trans-articular bridging is particularly useful in patients scheduled to undergo conversion to internal fracture fixation, as it protects the planned surgical approach from possible pin-tract infection around the screws of the primary tubular external fixator.

Surgical fixation in the treatment of severely injured, hemodynamically unstable patients should be rapid and minimally traumatic in order to avoid further aggravation of the patient's general condition and the local condition of the damaged limb. The gross displacement of bone fragments and local pressure on the skin and nearby neurovascular structures should be eliminated in the context of primary fracture fixation (Fig. 14.10).

In the treatment of patients with extensive wounds and exposed bone fragments, fixation using external frames is carried out, as a rule, at the final stage of primary surgical debridement. The technical difficulties of a fracture reduction procedure performed during the acute phase of treatment are usually insignificant, especially under open wound conditions involving an exposed fracture zone and bone fragments. In such cases, fracture reduction under direct visual and manual control is relatively easy.

Particular attention should be paid to the final position of the bone fragments achieved as a result of primary operative stabilization, especially when the condition of both the patient and the injured limb is relatively stable. Accurate positioning of the bone fragments during primary fixation is important, given that conversion from the primary external fixation frame to the final definitive internal fixation may be significantly delayed or even impossible in some severely injured patients [223]. This procedure, naturally, should be minimally traumatic.

Severe high-energy traumas usually result in extensive and deep tissue damage, and even tissue loss. Immediate restoration of the length and shape of the damaged limb is inexpedient and in some cases even dangerous. Early coverage of the exposed bone fragments poses a surgical challenge and frequently results in additional trauma. Significant wound defects demand the use of local and distant soft-tissue flaps. However, severe high-energy trauma causes extensive damage not only to the zone enclosing the wound itself but also to surrounding tissues. Thus, a precise definition of the extent and depth of the tissue damage is not possible during the early stages of treatment. Consequently, wound coverage using local or distant tissue flaps may become complicated by partial or even full necrosis of the flaps (Fig. 14.11).

Wound coverage using the microsurgical transfer of free tissue requires highly skilled specialist interventions and equipment but also imposes additional trauma to the donor site and a considerable lengthening of the operation time. Thus, in the severely traumatized patient this complex surgical approach cannot be reconciled with the vital principles of damage control. Instead, limb salvage using only the remaining tissues is advised to avoid any additional, even minimal, trauma in patients with severe high-energy injuries and extensive tissue loss, especially in those who are in critical condition, either generally or with respect to the injured limb. Temporary fixation of atypical bone fragments in positions of acute shortening, acute angulation, acute rotation, or a combination thereof create optimal conditions for the closure and healing of soft-tissue wounds, without additional morbidity to local or distant tissue flaps, and for free microsurgical tissue transfers. Care must be taken to avoid malpositioning of the bone fragments and possible neurovascular complications due to severe angulation and twisting of the main vessels and nerves. Therefore, estimating the level of the peripheral circulation is necessary after any "acute malpositioning" procedure (Fig. 14.12).

Cutting of the bone fragments is not obligatory in a significant acute limb shortening procedure. In some patients, especially those with femoral and humeral bones fractures, limb shortening is an option, with temporary superposition (duplication) of the bone ends. However,

Fig 14.9 (**a**–**e**) Trans-articular bridging fixation of the upper and lower limbs

Fig. 14.9 (continued)

resection of the bone ends is necessary in temporary tibial shortening, due to the tibia's exocentric position with respect to the surrounding soft tissues. If the intact fibula interferes with shortening and re-positing of the tibial bone fragments, fibular osteotomy or even its segmental resection are mandated.

An atypical position of the bone fragments, achieved at the final stage of the debridement procedure, allows the edges of the wound to be pulled together and thereby considerably reduces the extent of the post-traumatic soft-tissue defect. Thus, radical surgical debridement with temporary acute shortening, angulation, and malrotation of the bone fragments has been recommended in the treatment of severe open fractures with extensive soft-tissue loss, e.g., due to combat injuries, high-energy traffic accidents, and industrial trauma.

After complete soft-tissue wound healing (sometimes requiring an additional free skin graft on a relatively small area), graduated length restoration of the injured limb segment according to the Ilizarov method is possible. This treatment strategy allows preservation and restoration of the critically damaged limb using only minimally invasive methods of treatment and without causing additional local (damaged limb) and general (donor site) morbidity.

In addition, temporary acute limb shortening can be especially beneficial in the treatment of open complex fractures with vascular damage (Gustilo 3 C) and in limb fractures with complicated damage to peripheral nerves. Urgent vascular repair can be carried out without the need for grafting; the same is true for the nerves, as limb shortening allows the restoration of damaged vessels and nerves by a relatively simple end-to-end suture without tensioning. The results of this type of restoration, as a rule, surpass those achieved with restoration based on an interpositional grafting technique.

The surgical procedure is finished by repeated copious irrigation of the wound with antiseptic solution, followed, if indicated, by establishment of a drainage system.

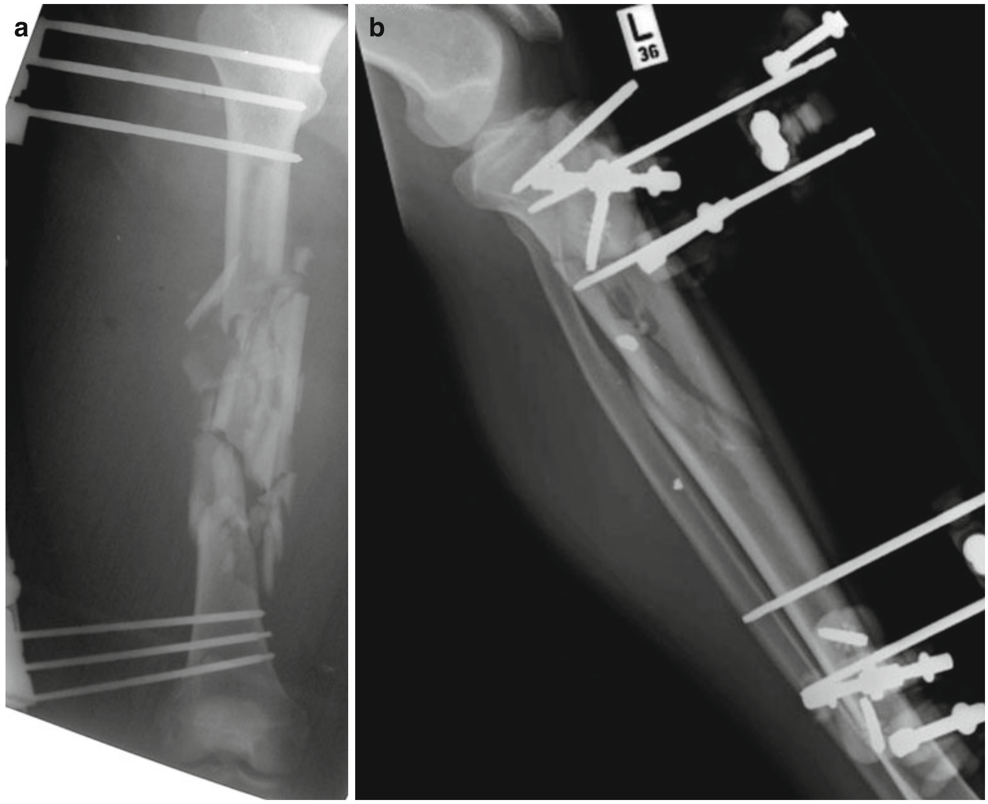


Fig. 14.10 (**a**, **b**) X-ray images obtained after primary fixation of the comminuted femoral and tibial bones demonstrate axial realignment of the bone fragments

Fig. 14.11 Tissue necrosis after a local rotating flap was used for coverage following extensive tissue loss resulting from a blast injury to the lower limb

In patients with high-energy injuries, especially combat-related gunshot and blast trauma, and in those with crush injuries, primary closure of the wounds must be avoided because of the high risk of contamination and the retention of necrotic tissues. Instead, standard care for the management of complex high-energy open fractures is initial surgical debridement, with the open wound covered with a traditional wet-to-dry dressing on the first day of treatment. Separate approximating sutures are allowed only for coverage of the exposed bone fragments using the surrounding muscular tissue (Fig. 14.13).

14.3 Final Bone Reconstruction Using Circular and Hybrid External Fixation Frames

Despite the above-mentioned advantages of unilateral tubular external fixators, these devices are limited with respect to their active influence on bone fragment positioning and the complex processes involved in bone callous formation and fracture healing. Indeed, unilateral tubular external fixation devices, as a definitive method of skeletal stabilization, have been associated with a high rate of non-union [224–226]. In most cases, as their name implies, these are only external stabilizing devices, yielding the same result as achieved by manual repositioning.

Alternatively, various methods of final fracture fixation are available. Conversion to internal fixation, including plating or intramedullary nailing, is the method of choice for the treatment of low-energy fractures. However, in patients with significant and extensive soft-tissue damage, any surgical intervention involving open repositioning and internal fixation of the displaced bone fragments will result in additional trauma to the injured tissues and disturb local blood supply. Internal fracture fixation in patients with problematic coverage of the bone fragments and the fracture site may considerably increase the probability of septic complications, especially in the presence of additional metal foreign bodies, i.e., the implanted internal fixation device. This is

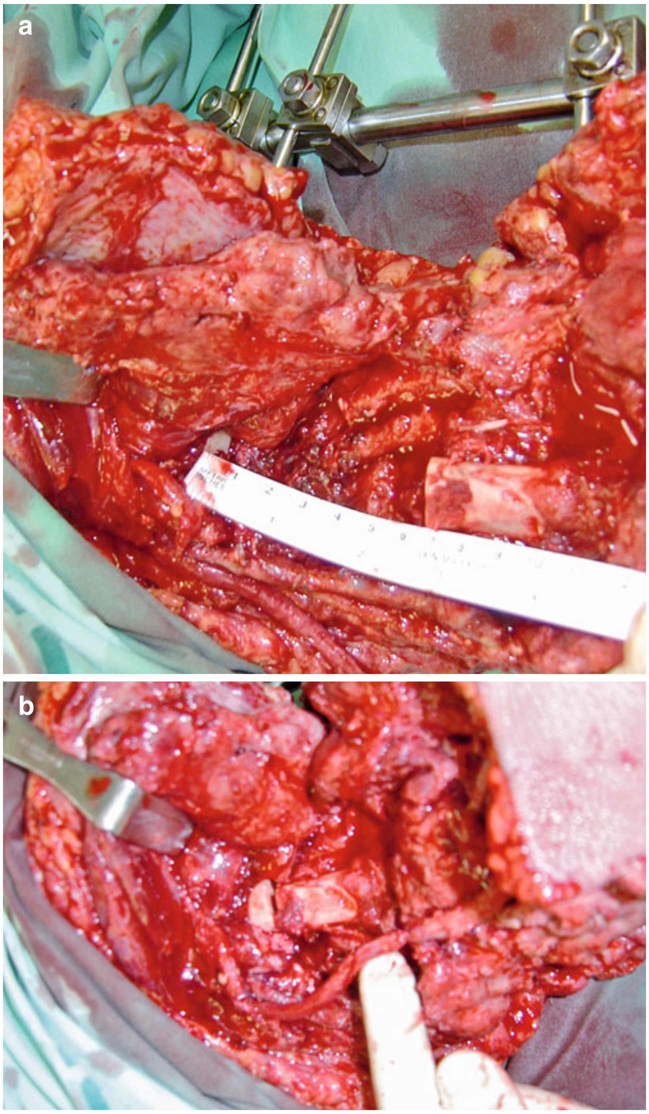


Fig. 14.12 Stabilization of an open humeral bone fracture in which there is extensive bone and soft-tissue defects and vascular damage (Gustilo 3C). (**a**) Radical debridement with temporary bone stabilization using a unilateral external fixation frame. The 6-cm defect of the humeral bone is seen. (**b**) Fracture fixation using a unilateral external fixator with the bone ends in a position of temporary shortening; reduction of the soft-tissue defect; and the establishment of conditions for wound coverage and vascular suture

especially relevant in the treatment of patients with combat trauma and victims of a terrorist attack. Continued treatment in both cases dictates the use of minimally invasive methods of external fracture stabilization using circular or hybrid external fixation devices.

When good fracture reduction was achieved in the primary operation, final fixation of the bone fragments should be performed as early as possible after the patient's general condition and that of the wound site have stabilized. In most cases, final fixation is possible 5–7 days after the trauma has occurred. It is usually combined with wound revision (second look) and with final coverage using plastic surgery methods.

Fig. 14.13 High-velocity gunshot injury to the elbow joint. Trans-articular bridging fixation using a tubular external fixator. The open post-debridement wounds are seen

Increased fracture stabilization with an external fixation frame is possible even if the position of the bone fragments is unsatisfactory. A final, precise fracture reduction procedure should be carried out only after soft-tissue wound healing.

Additional preoperative imaging of the damaged limb segment, including the adjacent joints, is mandatory to identify the position of the bone fragments, the proximal or distal extension of the fracture, missed fractures, and foreign bodies. Meticulous preoperative planning of the surgical procedure and the appropriate optimal fixation frame configuration offer the best chance of successful treatment.

The external fixation frame can be assembled by a variety of methods: (1) preliminary mounting of the frame prior to the operation, (2) mounting the fixation frame around the fixed limb segment during the operation, and (3) separate mounting of the proximal and distal fixation blocks followed by their joining together in the position in which the main bone fragments are to be re-aligned. We recommend preliminary assembly of the circular fixation frame, with stabilization of the tibia, forearm bones, and humerus. For the fixation of femoral bone fractures, we use the 2nd and 3rd options.

The number of rings, thin wires, and half-pins of the fixation frame varies depending on the type and configuration of the fracture, the condition of the soft tissues, and planned subsequent operative interventions. Temporarily bridged adjusted joints should be released during the conversion procedure.

Usually, the recommended distance between the internal part of the rings and the skin of the fixed limb should be within the limits of 2–3 cm. In the treatment of patients in whom severe post-traumatic swelling of the injured site is likely, and when additional operative interventions are

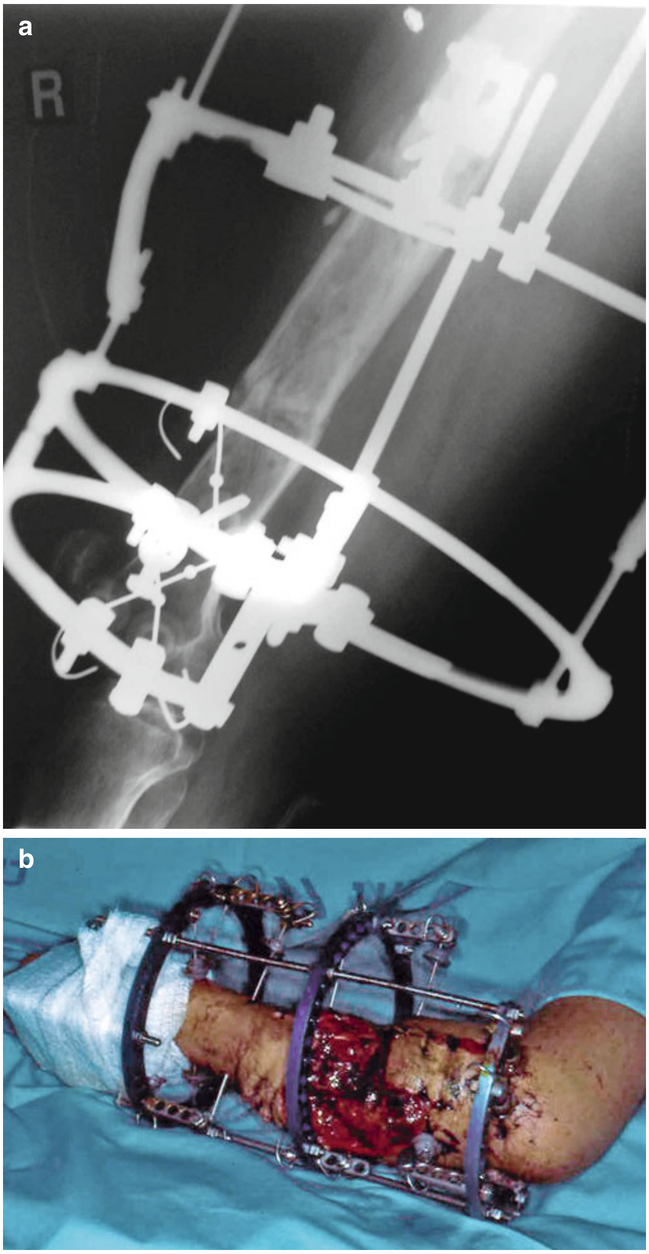


Fig. 14.14 (**a**, **b**) An Ilizarov large-ring external fixator is used to stabilize an open high-energy fracture with extensive soft-tissue damage

planned (plastic coverage procedures), this distance should be increased, especially on the posterior surface of the fixed injured segment. High-energy injuries are frequently associated with severe post-traumatic swelling of the injured limb. This dictates the need to use rings with a diameter larger than that usually recommended for the assembly of a circular frame in standard situations (Fig. 14.14). However, increasing the ring diameter reduces the frame's stability (Chaps. 2 and 3). To improve the rigidity of the fracture fixation, we recommend installing additional stabilizing elements in the frame and increasing the distance between the levels at which the half-pins and thin wires are inserted into the bone fragments. Moreover, single-plane orientation of the stabilizing transosseous elements should be avoided, if possible, according to the recommended positions (Chap. 5).

14.3.1 Conversion from Primary Unilateral External Fixation Devices with Half-Pin Preservation

In conversion procedures, it is desirable to preserve and use the Shanz screws of the primary frame, assuming there are no signs of local pin-tract infection, as they are well-fixed to the bone and situated in the recommended positions. These Shanz screws do not transfix either the muscles and tendons or the joint capsule. Screws located over tendon-muscle units, resulting in restricted joint motions, must be removed.

In most patients, circular Ilizarov devices or their analogues allow closed repositioning without the need for opening the fracture zone. Access to the bone fragments through a wound can facilitate fracture repositioning in patients in whom the closed reduction attempt was unsuccessful due to soft-tissue interposition. Open reduction is performed in these cases through the wound and maintained with clamps, or by applying thin wires through the reduced bone fragments for temporary fixation to maintain the fragments in the aligned position. 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.

During the conversion from the unilateral tubular external fixation frame to the circular Ilizarov external fixation device, it is important to preserve the good bone fragment reduction achieved during primary skeletal stabilization. For this purpose we recommend the following conversion technique: The tube of the double unilateral tubular frame that is more distant from the limb must be moved even further towards the outer ends of the half-pins and then firmly reattached. Then, the tube nearer the injured limb segment can be removed. These two steps provide adequate space for mounting a circular external fixation frame around the still fixed segment, preserving the previously achieved alignment of the bone fragments. The Shanz screws of the primary tubular external fixator are then firmly attached to the Ilizarov circular frame by fixing them to the corresponding rings. Additional thin wires and half-pins are introduced into the main bone fragments and included in the fixation frame. Then, while the stability of the fracture fixation is maintained, the remaining tube of the primary unilateral fixation frame is removed (Fig. 14.15). Following this sequence reduces both the hazard of secondary fracture displacement during conversion and additional trauma to the soft tissues, while shortening the operative procedure and minimizing both the patient's and the surgical staff's intra-operative radiation exposure. Moreover, part of this procedure (mounting the Ilizarov frame using the available half-pins of the primary fixation device) can be performed directly on the

Fig. 14.15 Conversion from a unilateral to a circular external fixation device. (**a**) External unilateral fixation of a high-energy tibial fracture; (**b**) conversion to the Ilizarov device with an additional foot ring to correct an equinus ankle deformity

hospital ward and without anesthesia. This considerably reduces demand on the operation room, which can be important in mass casualty situations such as war-related conflicts, natural catastrophes, and industrial accidents.

14.3.2 Hybrid External Fixation Devices

The simultaneous use of components from different external fixation (unilateral and circular) systems provides various options for external stabilization, exploiting the relative advantages of each type of external frame. The merits of unilateral external fixation devices include the simplicity of their design and their ease of use, their provision of sufficient access to the soft tissues of the injured limb segment, and the reduced inconvenience to the patient, especially in the fixation of proximal femoral and humeral fractures. Circular external fixators, on the other hand, provide reliable fixation, are suitable for full weight-bearing, and allow ongoing correction throughout the external fixation period as well as the reconstruction of large bone defects according to the Ilizarov method.

The use of hybrid external fixation frames expedites the fixation not only of diaphyseal but also of intra- and para-articular distal femoral, tibial, and humeral fractures, as well as proximal tibial fractures. The circular part of the hybrid device is placed above the metaphyseal zone, and the unilateral part above the diaphyseal zone (Fig. 14.16).

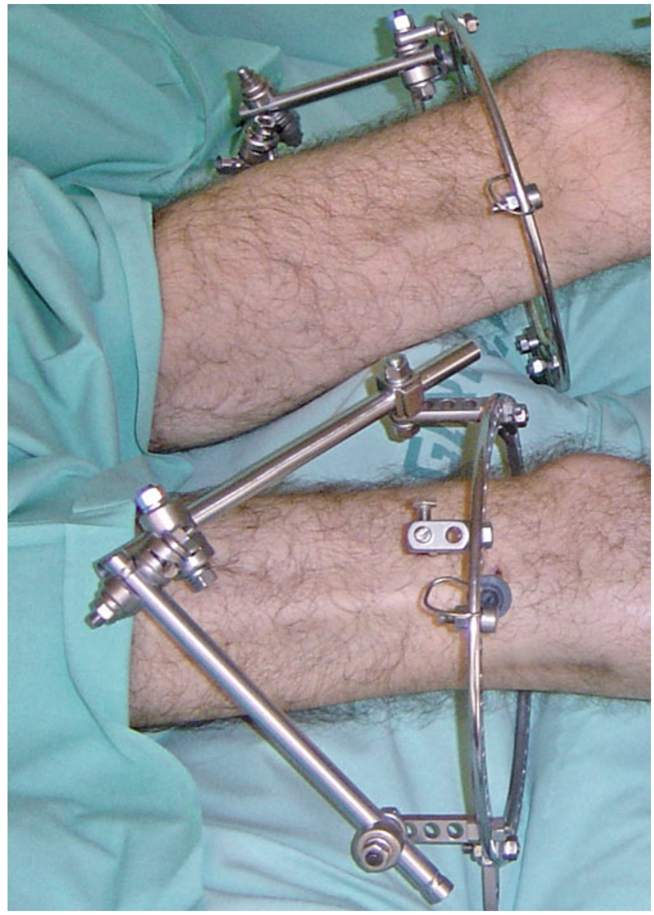


Fig. 14.16 Fixation of bilateral femoral fractures using hybrid external fixation frames

These standard hybrid frames, with one ring or a 5/8 ring above the metaphyseal zone, have a low rate of repositioning. This is advantageous because elimination of a secondary displacement or the continued correction of the bone fragments' position requires additional anesthesia and repeated manipulation of the injury in the operation room. The inclusion of an additional ring improves the repositioning capabilities of the hybrid external frame (Fig. 14.17). Threaded rods, located between these two rings, will allow, if necessary, bone lengthening by distractional osteogenesis, while threaded rods with hinges facilitate the repair of angular deformities, should they arise.

14.4 The Ilizarov Device as a Basic Frame

In a stage-by-stage treatment strategy, the conversion from a simple monolateral device to a circular one is not always necessary; rather, in some cases the Ilizarov device can be used for primary stabilization aimed at achieving damage

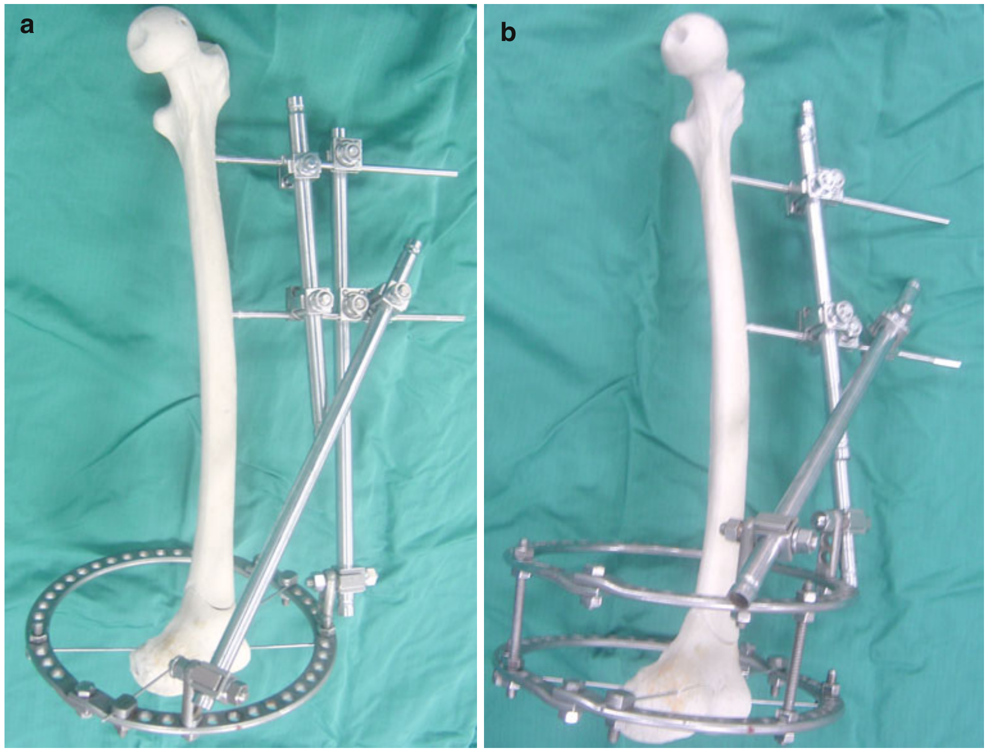


Fig. 14.17 Various configurations of hybrid external fixation devices. (**a**) The standard configuration has only fixation properties. (**b**) The two-ring frame allows dynamic influence of the fracture site

control. Unlike the installation of a monolateral frame, this variant of osteosynthesis should be performed by a specialist skilled in the Ilizarov technique. However, it is important that the same surgeon be involved directly throughout treatment of the patient.

The frame is originally mounted according to a minimum fixing scheme, based on only two supports, each of which is fixed using one or two transosseous elements (Fig. 14.18). Further information on the fixing variants of the Ilizarov device configurations is provided in Chaps. 10, 11, 12, and 13.

After the device has been installed, moderate distraction should be applied to increase the rigidity of the osteosynthesis and reduce the pressure exerted by the ends of the displaced bone fragments on the soft tissues. In this context, the fixation device is simple, convenient, and allows quick and effective primary stabilization of the fracture. Later, once the patient's condition has improved, final reduction of the displaced bone fragments and their stable fixation are carried out. This requires changing the primary configuration of the device by the inclusion of reductionally fixing supports and transosseous elements.

In addition to the above variant, a pre-assembled standard three- or four-ring device with one or two reductionally fixing rings can be used. Thus, at the first stage (during damage control) only basic transosseous elements are inserted. This method of frame installation facilitates the final reduction and fixation of the bone fragments. For this purpose it is sufficient to insert only the reductionally fixing transosseous elements.

It should be emphasized that these frame assemblies are suitable only for patients with Gustilo 1 and Gustilo 2 damage and for those with (multiple) closed fractures. In other cases, i.e., significant damage of the soft-tissue cover, the initial configuration should provide stable fixation of the bone fragments.

If external fixation is to be later converted to nailing, wires and half-pins are inserted such that they will not block the insertion of the nai (Chap. 26). Accordingly, in a femoral osteosynthesis it is expedient to use extracortical clamp devices (Table 1.2, Chaps. 12.5 and 26).

During the primary operation, final bone fragment reduction and stabilization using the Ilizarov apparatus can be carried out as long as the patient's condition allows (damage control) and the necessary organizational facilities are available, i.e., a qualified team and the required time in the operating room. The operation starts with the installation of the basic supports. In injuries to the proximal or distal bone segments, the basic supports are mounted only on the longer bone fragment. If the fixation of a joint is contemplated, the transosseous module is superimposed onto the adjacent segment. The exit sites of the transosseous elements are covered with a sterile drape and/or bandage.

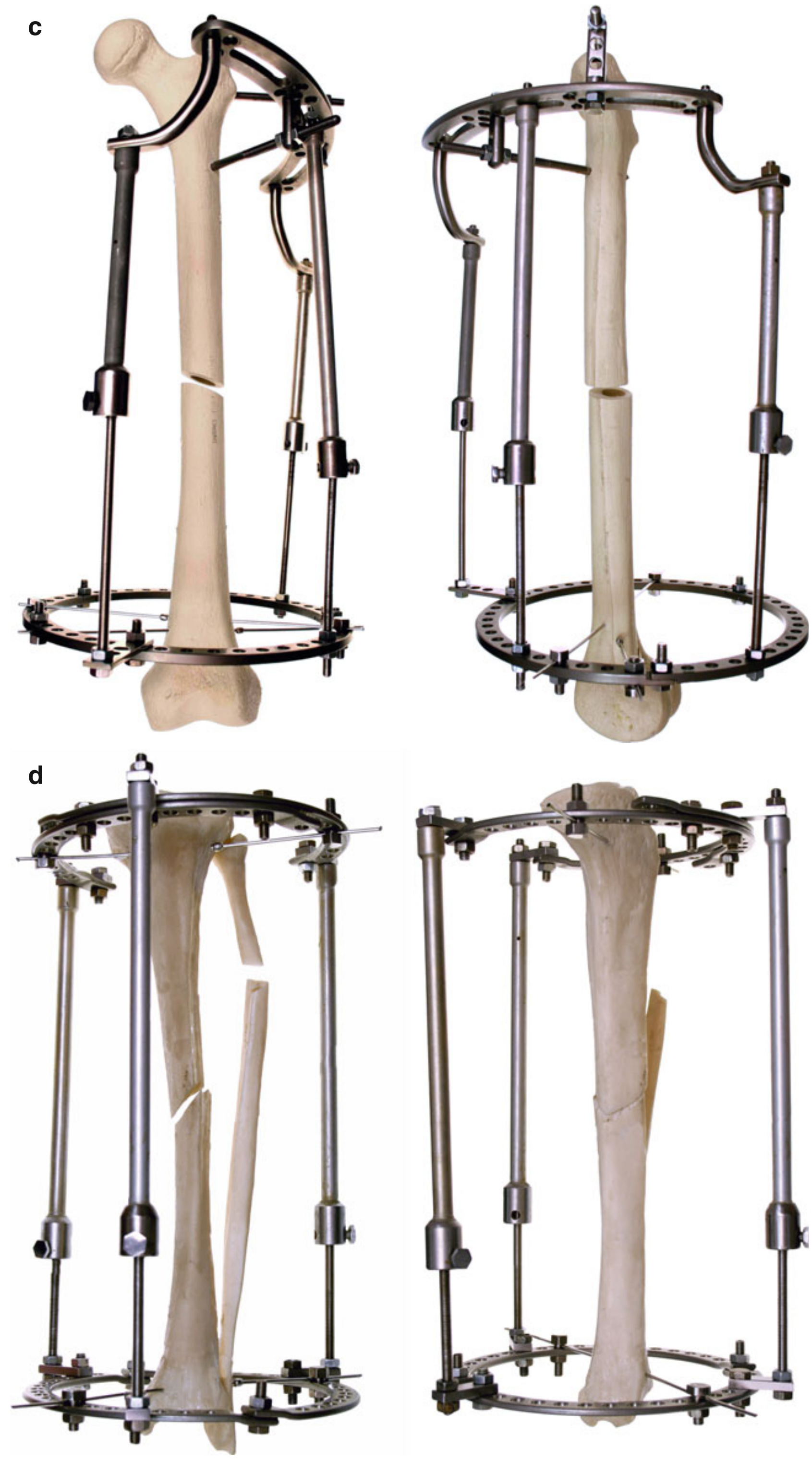
Using the basic supports as "bone-holders," the length and axis of the segment are restored without the repositioning or fixation of the bone fragments. This is necessary in order to determine the repair potential of the damaged major vessels (if not, the defect should be replaced with an autologous vein graft), nerves, muscles and tendons, with simultaneous preservation of the anatomic length of the segment. If repair is possible, then the next stage involves restoration of the damaged soft-tissue structure. During this stage of surgery, the basic supports are temporarily connected to two telescopic rods, and/or the main bone fragments are connected with the aid of diafixation using wires.

If arterial injury has led to non-compensated ischemia of the extremity, the main blood flow should first be restored.

Then, in compliance with the biomechanical requirements of the external fixation, the intermediate reductionally fixing supports are installed, with the number determined as needed. Under visual control, the main bone fragments

Fig. 14.18 (**a**–**d**) “Fixing” configurations of the Ilizarov device in shaft fractures. Note that the support and telescopic rods are connected with the aid of plates. This trick facilitates subsequent installation of the reductionally fixing supports These frame assemblies should be used only in patients with Gustilo 1 and Gustilo 2 damage and for those with (multiple) closed fractures

Fig. 14.18 (continued)



I,**5**-11 ↔ VII,**3**-9 (a)
I,**4**-10 ↔ VIII,**6**-12(VIII,6-12) (b)
I,8,90; II,11,90 ↔ VII,**3**-9; VII,2-8 (c)
I,**8**-2; I,**4**-10 ↔ (VIII,**8**-2)VIII,8-2; VIII,**4**-10 (d)

and splinters are repositioned and then stabilized in the device by insertion of the reductionally fixing transosseous elements. In splinter fixation, besides conventional wires console wires with a stop can be used.

As discussed above, the levels and positions available for the insertion of transosseous elements are limited in compound fractures. Therefore, in addition to the reference positions, safe positions, which avoid damage only to the main vessels and nerves, may be used more widely. Furthermore, to provide freedom of movement in the joints, some transosseous elements are best removed and replaced by new ones inserted according to the reference positions.

In a number of cases, in order to restore the soft-tissue structure without tension, including on vessels and nerves, the adjacent joint should be placed in a position that can be maintained during the postoperative period and will allow for the later removal of the soft tissues, for example with the lower leg bent. This can be achieved by installing a transosseous module in the adjacent segment based on one or two external supports. This module, installed with the aid of hinges in compliance with the rotational axis of the knee or ankle joint, is connected with the basic device fixing the bone fragments (Chap. 23). After the vessels and nerves have been repaired under microscopic control, the joint is gradually moved to the zero position. The hinges are stabilized after slight tensioning or "straightening" has been achieved [227]. Between days 14 and 21, graded movement is started in the joint in the direction that will cause tensioning of the sutured soft-tissue structures. The distraction force applied with the aid of the swivel hinged section is selected such that vessel and nerve stretching does not exceed 0.75–1 mm/day (3–4 times × 0.25 mm). Later, the hinge subsystem is used, when necessary, for the passive-active development of movement in the joint.

The above procedure generally enables the repair of damaged soft tissues, providing the defect is less than 50–55 mm. If modeling of both the length and segment axis restoration indicates that the diastasis will remain or considerable tension on the damaged soft tissues is required, or if there is wide segmented damage to the vessels and nerves (NV4) without the possibility of plastic repair of the defect, the above-discussed method of acute shortening (translation, angulation, torsion) can be used. Initially, the bone fragments are repositioned and stabilized in the device supports. The positions of the external supports and transosseous elements by which repositioning was achieved are documented in the medical records and photographically. The fragments are then given an "atypical" position to allow suturing of the soft tissues without tension. The possibility that a trophic disorder will ensue as a result of crimping or excessive bending of the major vessels should be borne in mind. The modules of the proximal and distal bone fragments are stabilized in the newly achieved position. This technique enables either suture repair or plastic repair of the damaged soft-tissue structures and secures the skin without tension. The combination of fixation of the adjacent joint in the desired position and rendering the fragments in an atypical position will reduce the degree of deformity of the damaged segment.

When, during debridement, bone defects occur in a segment, the assembly of the transosseous device must provide for the possibility of restoring the lost tissue. In such cases, monolocal and bilocal methods of external fixation can be used [228, 229]. During debridement, the ends of the fragments must be processed for their adaptation, if need be.

In monolocal distraction osteosynthesis, the proximal and distal bone fragments are simultaneously approximated until they are in close contact. Within 14–18 days, the bone fragments are gradually separated at a mean rate of 0.25 mm three or four times a day until the segment length is restored (Fig. 14.19b, c). If the fibula hinders the approximation of the femoral fragments, fibular osteotomy or segment removal is warranted. In the forearm, the monolocal method of distraction osteosynthesis can be used only if the two bones show similar defects.

In some cases, simultaneous approximation of the main bone fragments is not possible. This is particularly likely if there is evident crimping of the soft tissues, resulting in trophic disorders and hindering wound suturing. In these cases, monolocal successive compression-distraction osteosynthesis is used. The bone fragments are gradually approximated after the skin wound has healed. However, the rate of approximation is limited by the neurotrophic disorder and usually does not exceed 3–5 mm/day in four to six sessions. After the bone fragments have been approximated, they are compressed axially or laterally depending on the plane of the bone wound. Within 14–18 days, the bone fragments are gradually separated at a mean rate 0.25 mm two or three times a day until the segment length is restored (Fig. 14.19a–c).

If by the end of the distraction period there are signs of soft-tissue tension that can be attributed to the tension caused by the transosseous elements fixed in the reductionally fixing supports, those elements should be replaced. For example, in Fig. 14.19, half-pin V,8,90 is replaced with wire VI,**9**-3.

In the case of a marginal, triangularly shaped defect, the segment is given an angular deformity until the fragment wound surfaces are in contact. The transosseous modules fixing each bone fragment are connected with two axial and one swivel hinge. On postoperative day 7–10, gradual distraction is started in order to form a triangular regenerate. For simultaneous elongation, a trapezoidal regenerate is formed. Further details on the formation of wedge-shaped distraction regenerates are presented in the sections of this book dedicated to traumatic deformities and the transosseous osteosynthesis of pseudoarthroses.

If the bone needs to be moved a greater distance, then during the debridement an axial wire or flexible pulls should be inserted (Chap. 19). When the relocating support has reached its limit of movement, the transosseous elements fixed in it are removed. Further relocation of the fragment is performed

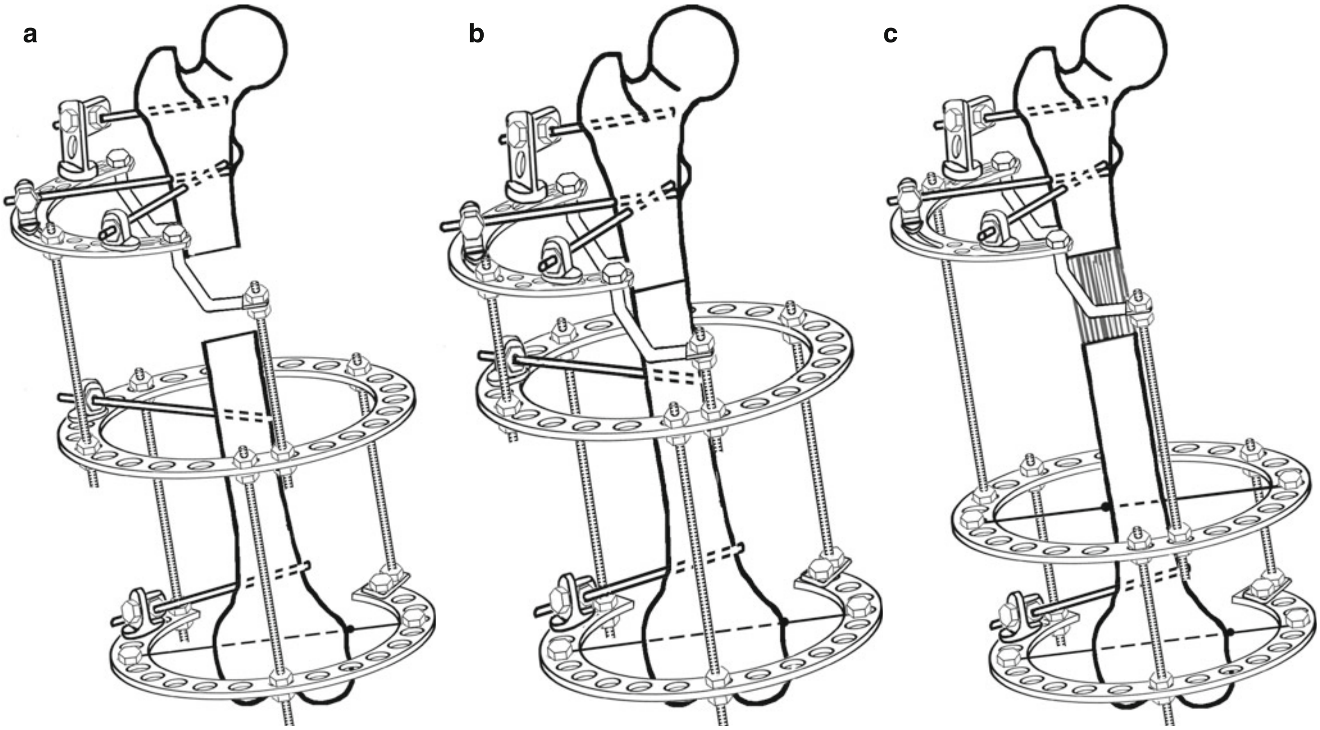


Fig. 14.19 (**a**–**c**) Examples of open monofocal distraction (**b**, **c**) and alternating compression-distraction (**a** → **b** → **c**) for external fixation in the treatment of a segmental defect of the femur

with the axial wire (or flexible pulls). Traction-guiding wires are inserted immediately prior to the removal of the transosseous elements of the intermediate support. The magnitude of the traction to be applied to the traction-guiding wires to enable linear relocation of the intermediate bone fragment by 1 mm is determined by calculations based on radiographic information [9, 25, 230].

More detailed information on bilocal compression-distraction osteosynthesis is presented in Chap. 19.

Figure 14.20 shows an example of tibial bone defect replacement after an open (Gustilo 3b) fracture of the right lower leg.

When the bone fragments are covered by muscles but there is an extensive skin defect, the method of choice is that of Ilizarov, which involves replacing the skin of the defect. At each wound margin, a Kirschner wire is inserted and then fixed with pulling and distraction clamps to the device supports (Fig. 14.21). In the postoperative period, the wound margins are gradually approximated (0.25 mm × 3–4 times a day) until they can be stitched together.

14.4.1 Special Features of the Ilizarov Circular Device in the Treatment of Open Peri-articular Fractures

Severe trauma to the major joints, especially the knee and elbow, is common in combat injuries [231]. These high-energy injuries are usually associated with massive soft-tissue damage as well as ligament and capsular tears [232]. Reliable stabilization of the bone fragments using hinged external fixation frames that enable simultaneous early motion optimizes the functional outcome of these complex injuries. Generally, the stabilization of open articular fractures is carried out according to the principles stated in Chaps. 2, 7, 10, 11, 12, and 13.

The joint's stability should be examined during the final stage of the fracture fixation procedure. If articular instability is noted, the external fixation frames from the different sites of the joint should be connected using axial hinges.

The specific features of articular hinge installation for the different joints are described in Chap. 23. Improper setting of the hinges and discrepancies with the rotational axis of the fixed joint will result in displacing forces during movements, causing damage to the cartilage, articular capsule, and ligamentary complex as well as secondary bone fragment displacement and even subluxation of the fixed joint.

The setting procedure at the axial hinge should start from one side of the injured joint (internal or external), without firm attachment of the hinge to the corresponding proximal and distal rings of the external device. If control movements at the joint result in hinge displacement, then the location of the hinge must be changed, moving it to the next set of apertures on the rings, with this dynamic test then repeated. Only after the hinge is firmly fixed to the corresponding proximal and distal rings is the same procedure repeated on the

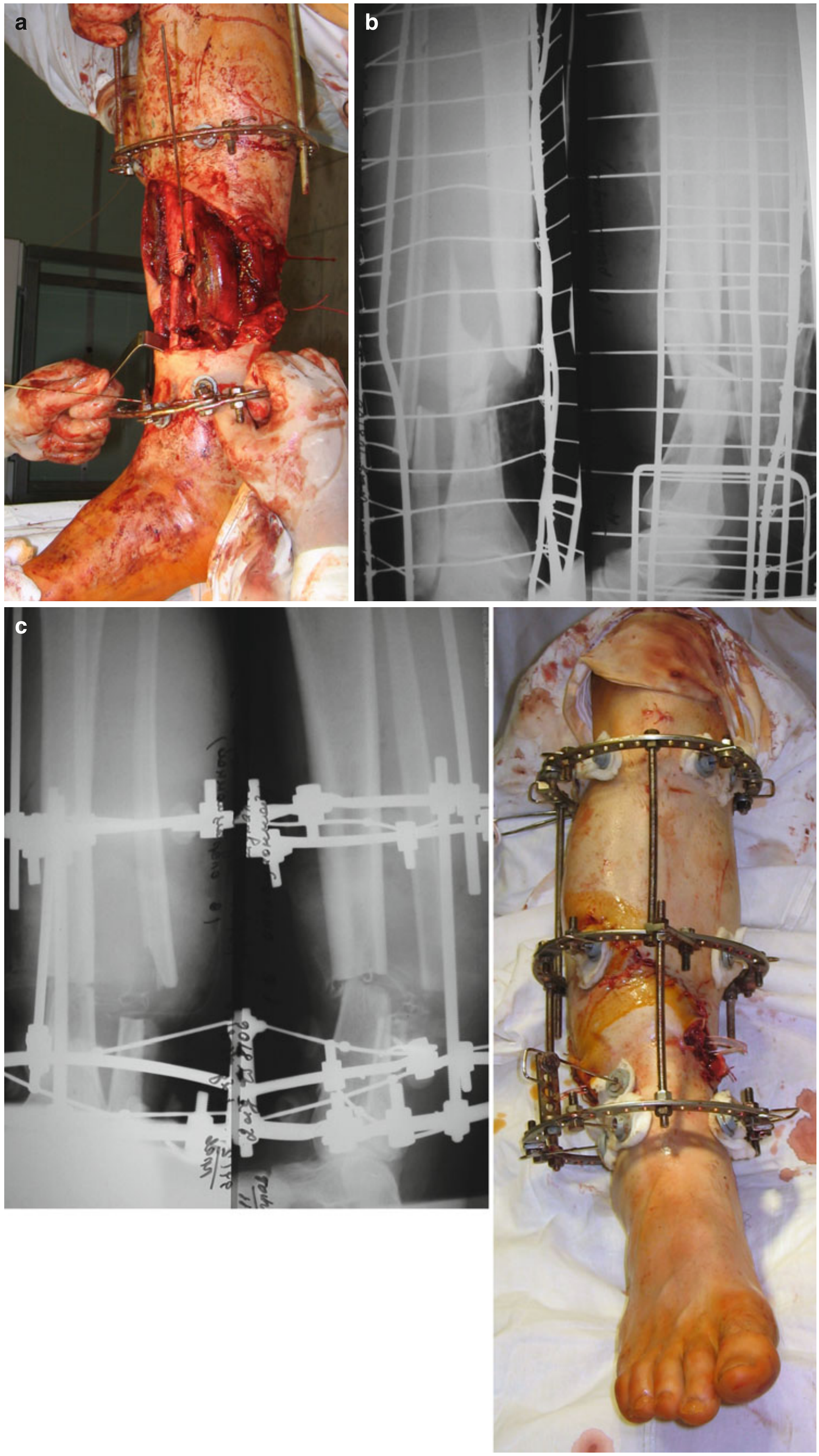


Fig. 14.20 (**a**–**h**) Acute shortening in the treatment of a tibial and soft-tissue defect. (**a**) Initial radiological image. (**b**) Initial view of the lower leg. (**c**) After debridement, external fixation and acute shortening

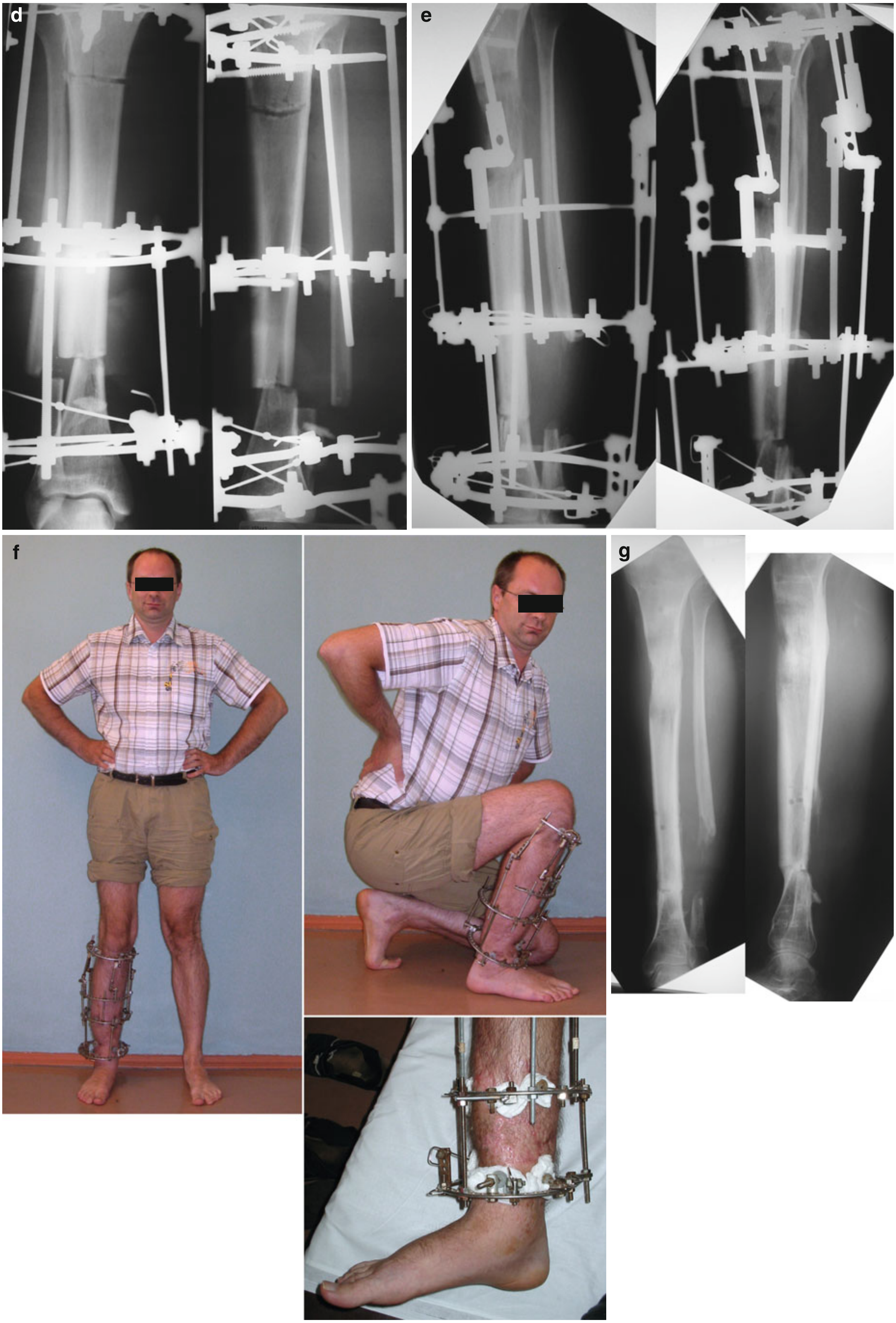


Fig. 14.20 (continued) (**d**) A corticotomy was performed on day 12. (**e**) 6 cm lengthening. (**f**) During the fixation period. (**g**) The index of fixation was 35 days/cm.

Fig. 14.20 (continued) (**h**) Two weeks after frame removal

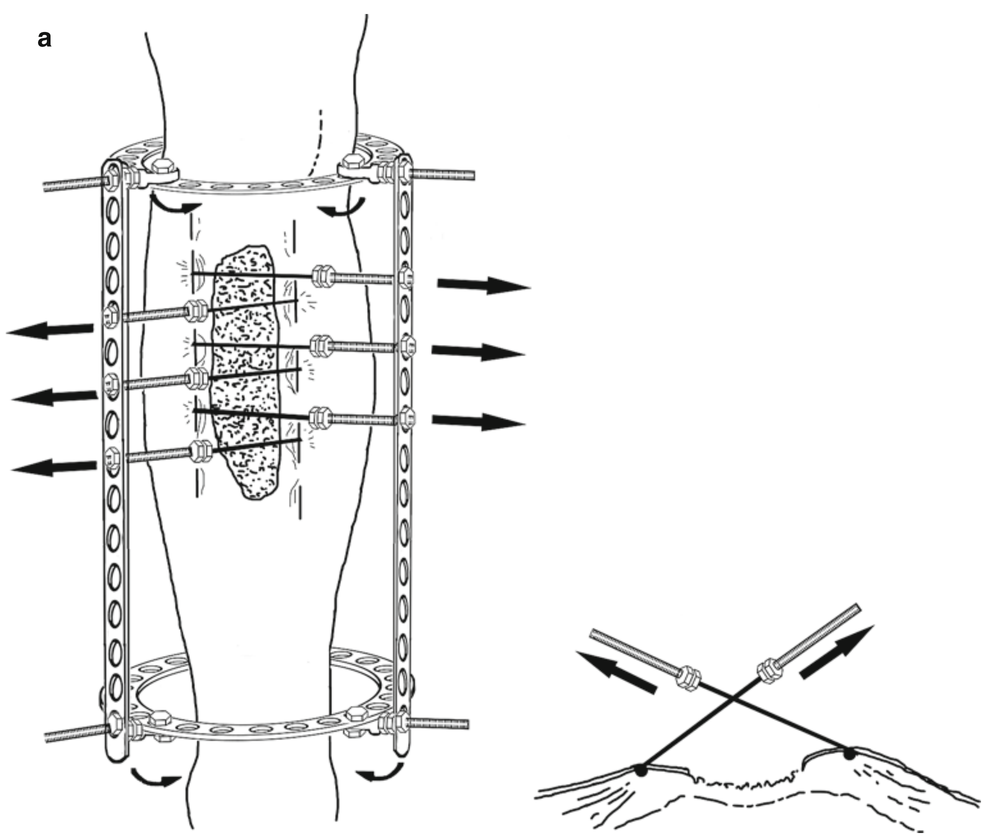


Fig. 14.21 Ilizarov method in the replacement of a skin defect. (**a**) The surgical strategy

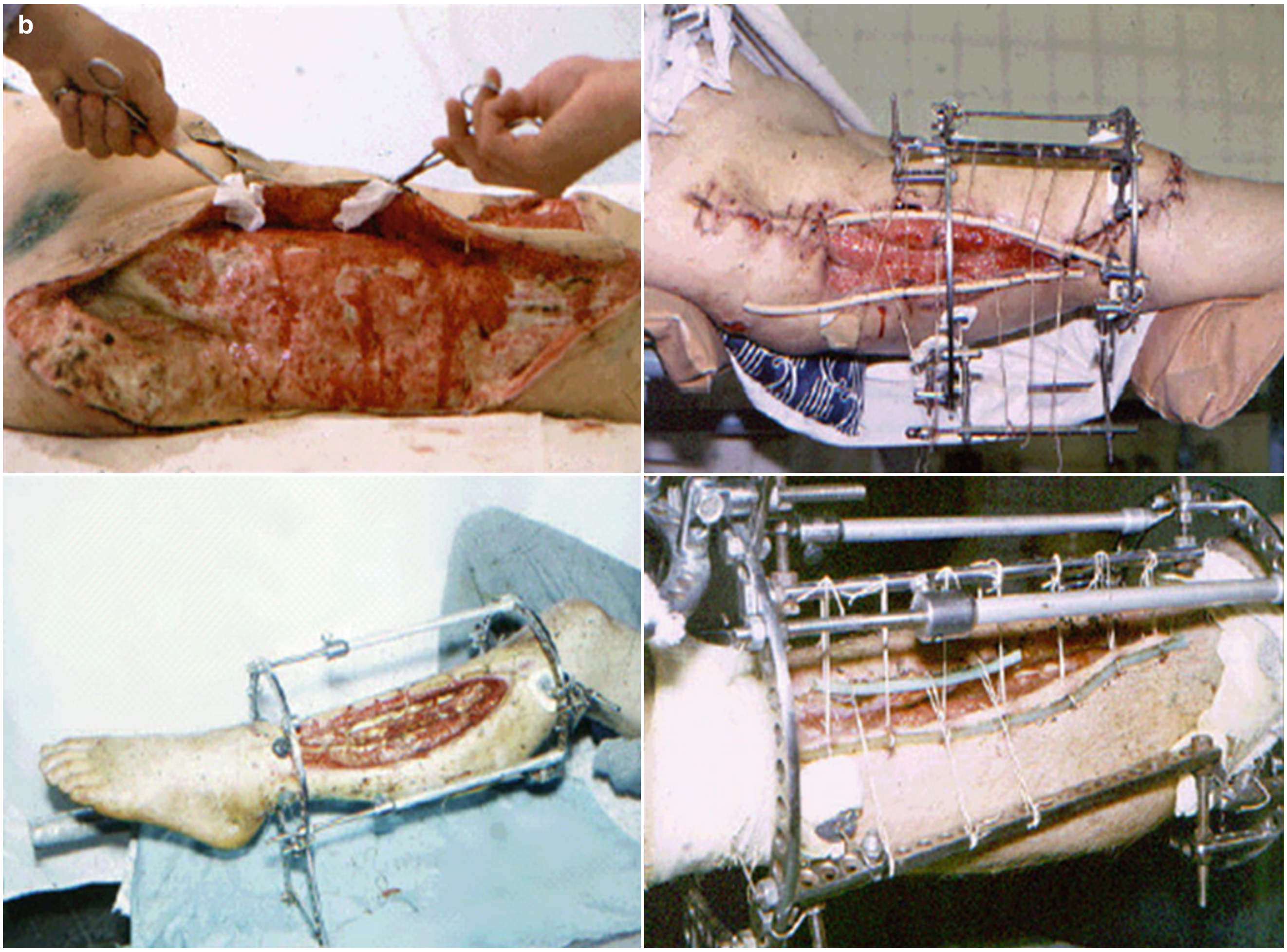


Fig. 14.21 (continued) (**b**) S.I. Swed's clinical images

opposite side of the trans-fixed joint. The use of either radiography with contrast labels or intra-operative fluoroscopy facilitates this technically demanding procedure.

Articular distraction resulting in a diastasis of 2–4 mm is needed to prevent the articular surfaces from damaging each other by axial compression of the bone fragments. Stable fixation in the device with correctly located axial hinges allows early active and passive movements in the joint, providing partial axial loading on the damaged limb. The range of these early active and passive movements exercises is as tolerated, avoiding pain. Sometimes, extensive damage to peri-articular soft-tissues, including the articular capsule and ligamentary complex, dictate a delay in the early mobilization of the injured join. Restoration of the maximal possible range of movement following complex intra- and peri-articular fractures requires significant effort and time, both during the external fixation period and after removal of the device. Trans-fixation of the soft tissues in the external fixation frame leads to some restriction of movement in the adjacent joints, which will remain until the transfixing elements (thin wires and half-pins) are removed (Fig. 14.22).

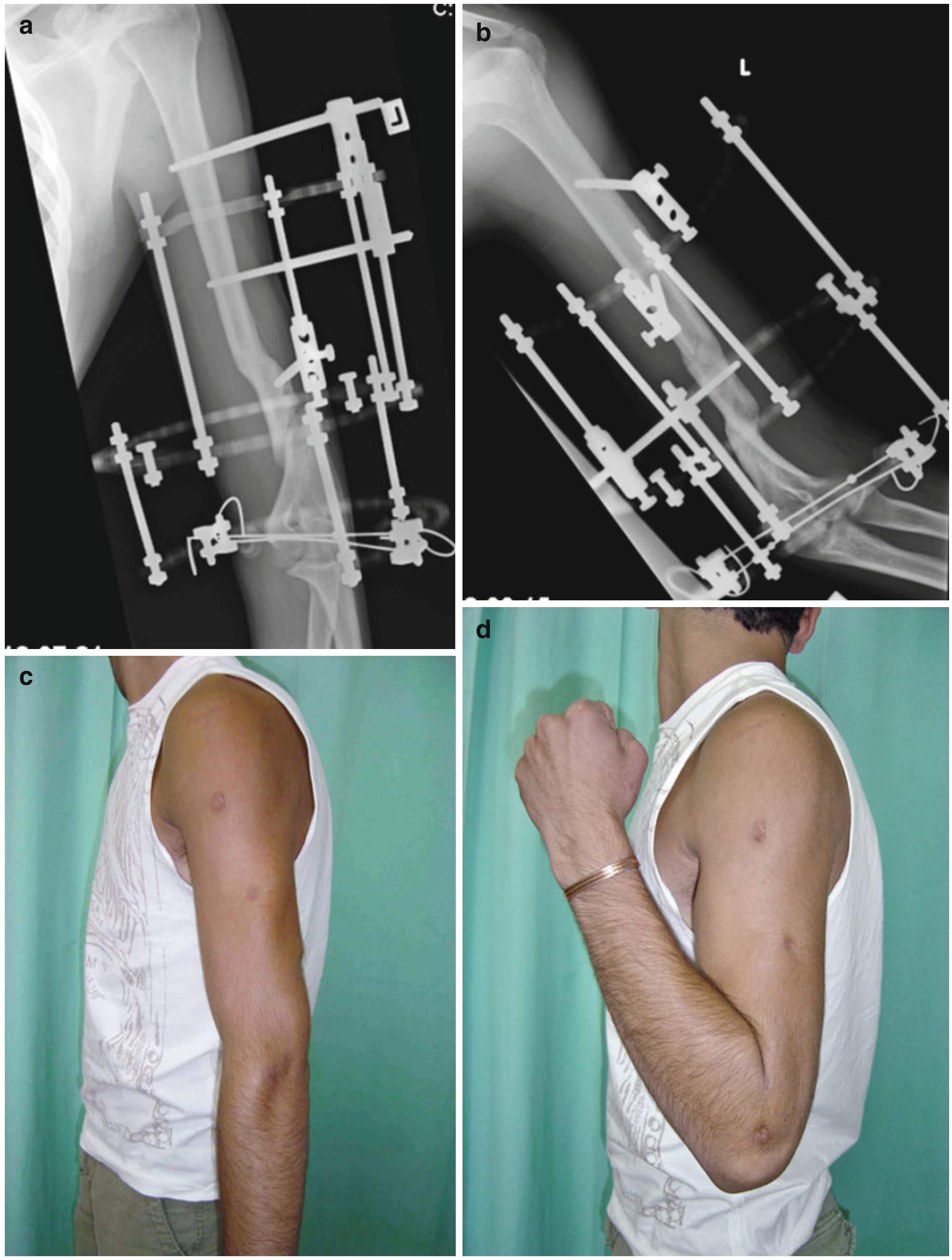


Fig. 14.22 Use of the Ilizarov frame in the treatment of a comminuted humeral fracture caused by a gunshot. (**a**, **b**) X-ray images obtained during the period of external fixation show significantly restricted elbow-joint flexion. Intensive physiotherapy was started during fixation and continued after removal of the Ilizarov frame, (**c**, **d**) Six months after the removal of the circular external fixation frame the patient has achieved full range of movement of the elbow

14.5 Universal Reduction Units

Bone fragment reduction based on the use of "basic" and "reductionally fixing" supports and transosseous elements was discussed in previous chapters. Changes in the spatial location of the bone fragments in these settings are achieved by moving only the transosseous elements that fix the bone fragments; the external supports and the device modules remain immobile (Chaps. 1.5 and 2.2.2). The use of bent wires and/or wires with stops, "half-pin pullers," and "half-pins pushers" is a classic approach in external fixation and, owing to its high efficacy, frequently employed for fracture repositioning.

The methods used to change the spatial orientation of bone fragments by moving the transosseous modules are described in detail in Chaps. 2.2.1 and 16 (Figs. 2.4, 2.5, 2.6, 2.7, 2.8, and 2.9). An orthopedic surgeon should stably fix the proximal and distal bone fragments. The proximal and distal transosseous modules are then connected with the aid of a unified reduction

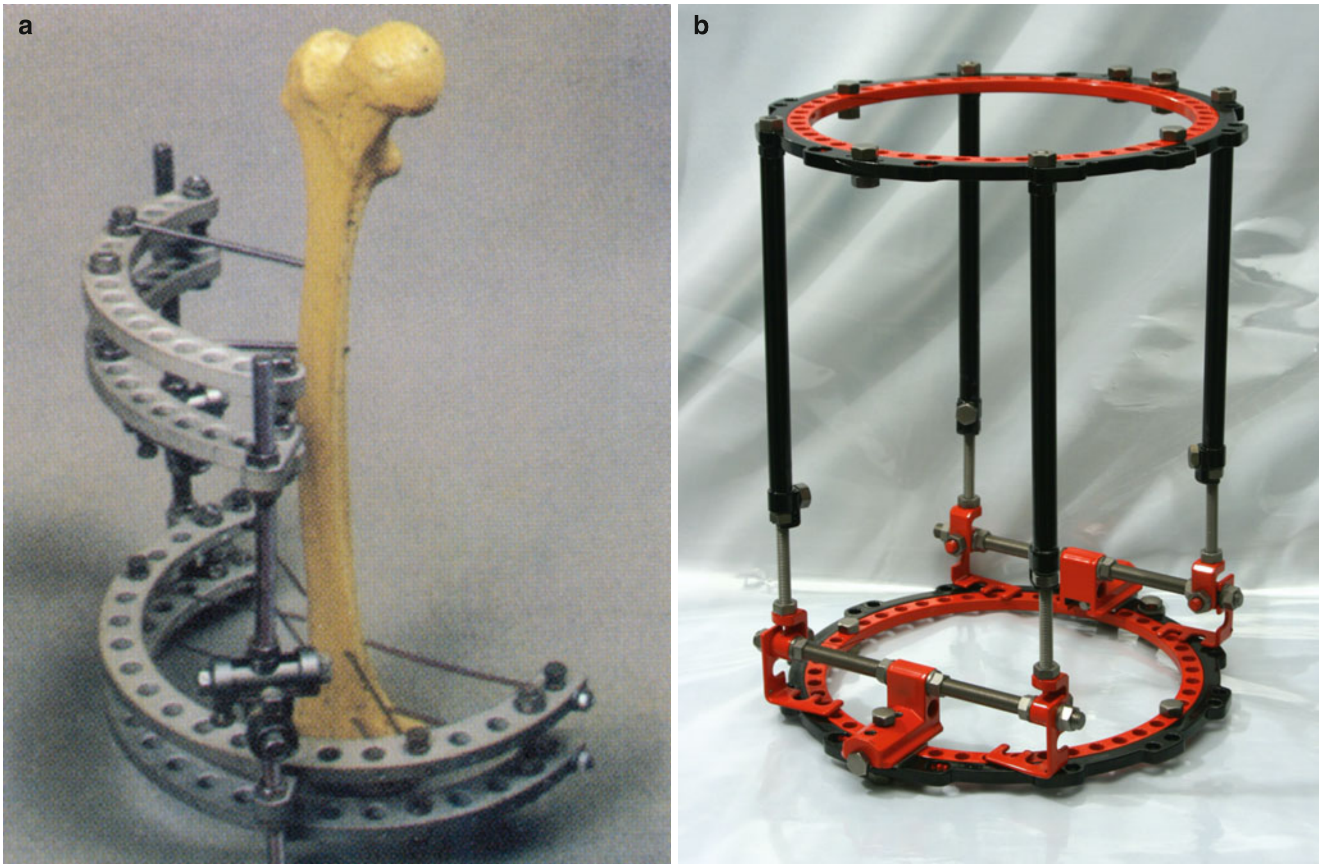


Fig. 14.23 External fixation devices with universal reduction units. (**a**) The Oganesyan device and (**b**) the Matsukidis-Shevtsov device

unit appropriate for the elimination of a transverse translation, angle translation, or torsion translation. Multi-component displacement reduction units should be replaced. This method is difficult and demands an experienced specialist for its execution. For this reason we recommend that, at least initially, fractures, including open fractures, should be treated with reduction and fixation "inside a frame" (Chap. 2.2.2). However, the configuration of a reduction device based on mutual displacement of the modules (Chap. 2.2.1 and 2.8) is in most cases less bulky. Moreover, this approach to bone fragment reduction is advantageous in acute shortening, acute angulation, acute rotation, and the combination thereof.

It is possible to solve this contradiction using external fixation devices based on universal reduction units, for example the Oganesjan and Shevtsov-Matsukidis devices [233] (Fig. 14.23). The disadvantages of these frames are their limitations in achieving osteosynthesis of the proximal parts of the humerus and femur and the necessity of repeated radiological control at all stages of the reduction.

External fixation devices controlled by computer navigation, so-called hexapod devices (Fig. 1.2p–r), including the Ortho-SUV Frame (Chap. 17), solve this problem at a qualitative level. Figure 14.24 shows the use of the Ortho-SUV Frame in the treatment of a patient with a complex atypical position of the bone fragments.

Conclusion

The severe general condition of the patient with a complex high-energy injury often results in extensive tissue loss and thus a high rate of complications. In these patients, an early multi-surgery approach cannot be reconciled with the basic principles of damage control. Instead, a staged treatment protocol based on minimally invasive methods and performed according to damage control principles will enable the preservation and functional restoration even of limbs at risk. The Ilizarov method provides rapid and minimally invasive stabilization regardless of the fracture configuration. Moreover, unlike methods of internal fracture fixation, the Ilizarov device allows, if necessary, the gradual elimination of bone fragment displacement, while stabilizing the fixation and creating the conditions for the repair of extensive bone and soft-tissue defects.

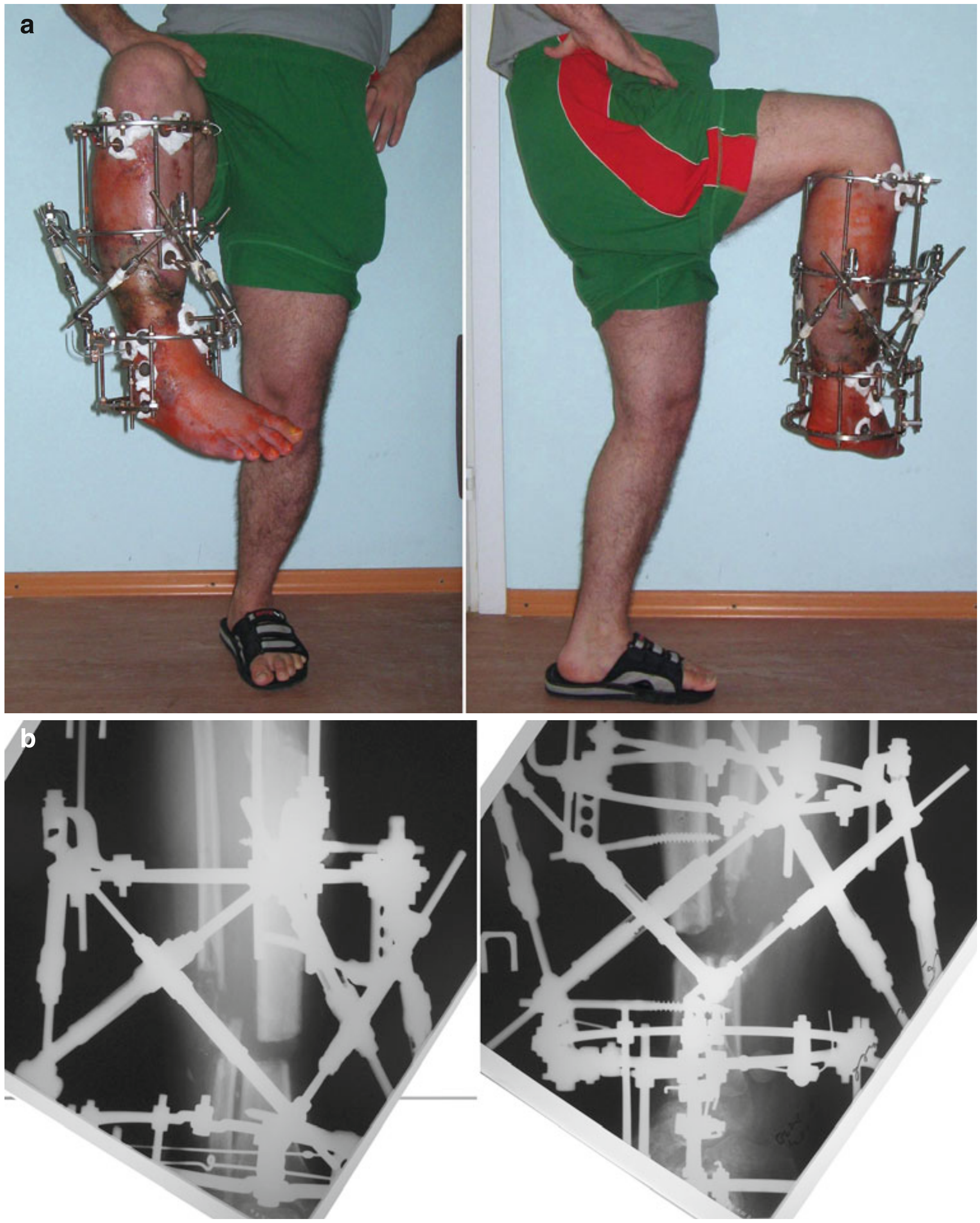


Fig. 14.24 Use of the Ortho-SUV Frame in the treatment of an open fracture of the lower leg. (**a**, **b**) Acute rotation + angulation + translation provide optimal conditions for soft-tissue healing

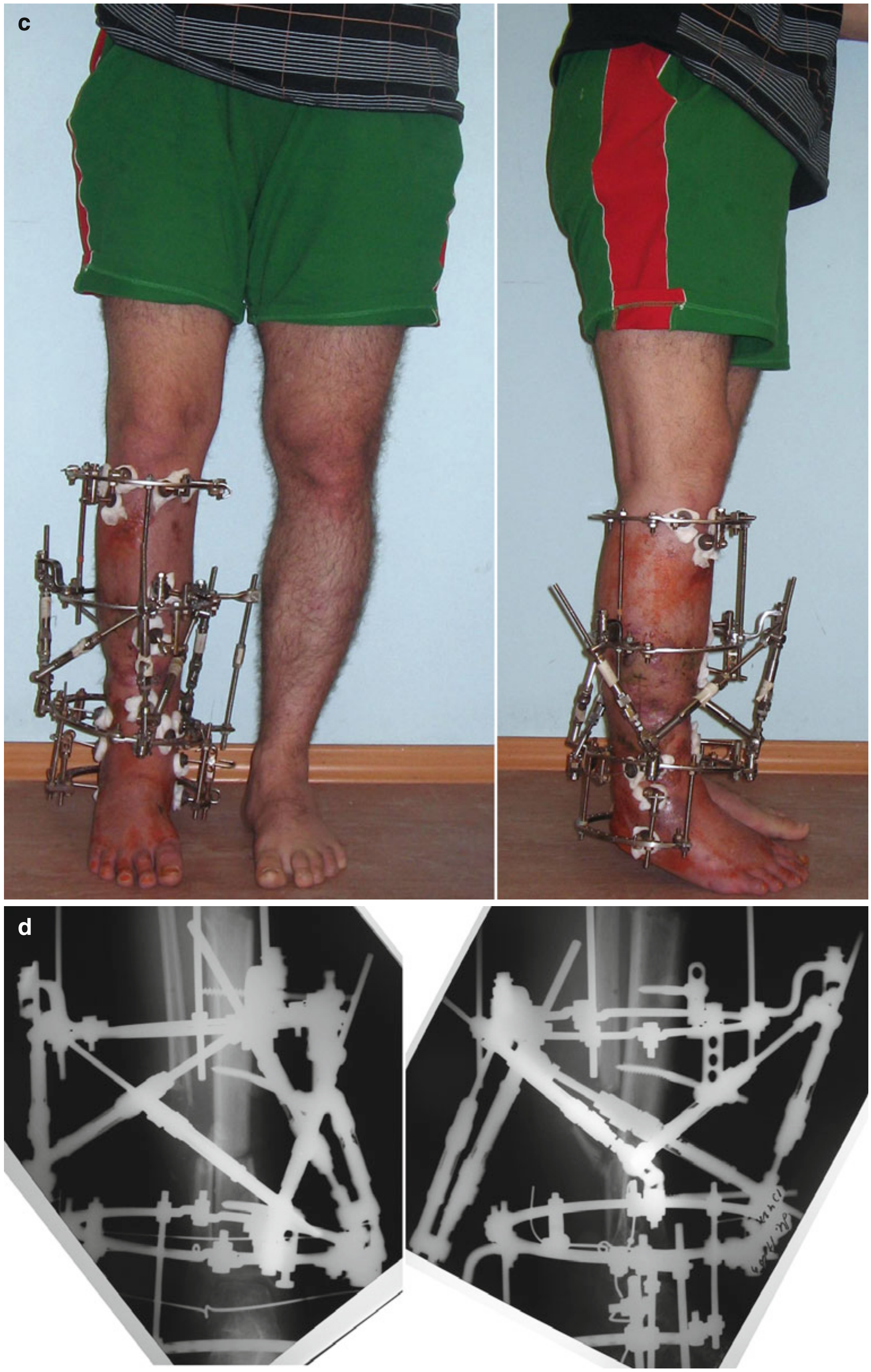


Fig. 14.24 (continued) (**c**, **d**) All components of the purposely created deformity are eliminated using the “integrated” trajectory, omitting the need for the stage-by-stage replacement of Ilizarov reduction units