A. Lerner · D. Reis · M. Soudry

Severe Injuries to the Limbs

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Staged Treatment

With 804 Figures, Mostly in Colour

Springer

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This book is dedicated to our wives Galina Lerner,
Batsheba Rosental-Reis, and Esther Soudry,
without whose understanding and support
it would not have seen the light of day.

Foreword

Polytrauma is a disease of our modern high-speed society. Most cities have designated trauma centers that administer to individuals with multiple injuries. Most trauma centers are not prepared, trained or equipped to treat the severity of injuries or number of patients that present from terrorist or war trauma. This book presents an authoritative organized comprehensive approach to orthopedic war injuries of bone and soft tissues. Dr. Alexander Lerner is one of the foremost authorities in the world in this field, working at Rambam Hospital in Haifa, where geo-political circumstances have delivered civilians and military personnel injured at war or from terrorism to the hospital's doors. While various fixation methods are presented, innovative methods using external fixation are the centerpiece of this book. Some of these techniques provide orthopedic surgeons with methods to avoid the need for extensive plastic surgery procedures by using the external fixators' abilities to reposition the bone fragments. The techniques of bone transport, fracture and nonunion distraction as well as various soft-tissue reconstruction methods are discussed, illustrated, and taught in detail.

This book is an essential guide for today's trauma centers that deal with urban warfare and for many urban hospitals and orthopedic trauma surgeons that may be called upon to treat mass casualties due to accidents or terrorism. Military surgeons will use this tome as a guide book for the treatment and reconstruction of war-injured patients. This unique book is the unfortunate product of our insecure world but by the same token is essential for the survival of those unfortunate enough to be traumatized in today's world conflicts. This book is well written and illustrated with numerous photographs, radiographs and illustrations.

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Preface

The treatment of severe locomotor system trauma has a long tradition in our hospital, the Rambam Medical Center, Haifa, the only tertiary hospital in the north of Israel covering a population of almost 2 million citizens. Our hospital lies less than 20 min helicopter flying time from the border, and hence, sadly due to the ever-present outbreaks of war and terror in the north of Israel along the Lebanese and Syrian borders, our trauma and orthopedic teams have accumulated vast experience in the treatment of severe injuries of the musculoskeletal system. As the major referral center for all the hospitals in the north of the country, the orthopedic and trauma departments take in civilian and military patients suffering from complex primary or secondary orthopedic trauma.

This book summarizes the authors' accumulated experience in the treatment of severe wounds of the limbs. The constant stream of major military and civilian trauma has afforded us the opportunity to develop our staged method. Without exception, all the cases reported in this book that demonstrate our staged treatment are taken from our own archives.

Sophisticated techniques for the care of massive injuries to the soft tissues and the most modern devices and methods for the fixation of severe fractures have been integrated into our treatment protocols. The staged treatment protocol, based on minimally invasive external fixation and the biological principles of tissue reconstruction by distraction tissue genesis (the versatile Ilizarov technique), permits the reconstruction of severely injured limbs and at the same time avoids serious complications.

In this monograph we report on the accumulated experience of 40 years in the treatment of severe injuries of the musculoskeletal system with grave tissue loss, and in particular war injuries. Emphasis is given to the proper attention and care of the soft tissues, sequential damage control, and the judicious staged use of appropriate external fixation.

The authors wish to thank and pay tribute to the relentless day and night work of all the devoted surgeons and nurses who have participated in the care of our patients over the years; in particular, the residents, senior orthopedic surgeons, and previous and current heads of the orthopedic departments at Rambam Medical Centre, without whose devotion and dedication this work could not have been done. We wish, in particular, to pay a special tribute to Professor Haim Stein, Emeritus Associate Professor, and former director of the Department of Orthopedic Surgery A. Professor Stein promoted, stimulated, and himself took part in limb salvage surgery until his retirement. He deserves much credit for the evolution of our staged method of treatment which depends so much on the principles of external fixation.

In conclusion, we hope that this book will be helpful to orthopedic, trauma and military surgeons treating severe high-energy limb trauma, especially limb salvage in severe war injuries, and elective limb reconstruction surgery and rehabilitation. We dedicate this book to our patients, without whose courage, fortitude, and motivation to be rehabilitated, our attempts would not have been successful.

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Introduction

1

In recent decades, the number of injuries caused by high-energy trauma has increased significantly due to the greater number of severe road traffic accidents, work trauma, and also firearm and blast injuries due to local military conflicts and terror attacks. More than 75% of all injuries in modern warfare are to the extremities, with a high risk of deep wound infection and post-traumatic osteomyelitis (caused by free bone fragments stripped of their periosteum), severe covering-tissue defects, and concomitant vascular injuries [16]. In recent local regional conflicts, there were relatively fewer thoracic and abdominal injuries but more damage to the extremities, due to the use of body protective vests. In road traffic accidents, modern safety equipment, such as seat belts and airbags, has changed the pattern of injuries, protecting the head and vital organs of the trunk. However, the extremities, especially the lower ones, are exposed to injury, and often suffer complex fractures [86, 135]. The number of multi-trauma patients reaching emergency rooms alive has increased, thanks to the fact that more emergency medical and paramedic teams are trained to cope with life-threatening critical conditions, and due to the rapid evacuation of battlefield casualties and victims of terror attacks to trauma centers that provide the required care immediately.

High-energy injuries to the limbs, involving both bone and soft tissue, remain complex injuries to treat, especially when associated with life-threatening injuries [2]. This is highly relevant to war injuries, especially blast injuries, which, by their high-energy impact, cause extensive blunt soft-tissue injury due to the blast wave, multiple penetrating fragment injuries, heavy contamination of the tissues, and a high rate of compartment syndrome. According to Nechaev et al. [99], most of the injuries in the Afghanistan war were multiple and complex (59.4%–72.8%), and more than half the injured were admitted in severe and critical condition. The management of open fractures is challenging, and multiple complex surgical procedures are frequently needed to achieve soft-tissue coverage, fracture union, and restoration of function [146].

Traditionally, firearm injuries have been divided into high- and low-velocity categories, based on projectile muzzle velocity. Low-velocity missile wounds are more common in the civilian population, and are typically caused by projectiles with a muzzle velocity of less than 610 m/s or 2000 ft/s (mostly handguns). They cause less tissue destruction and generally the injury can be treated after wound excision by closed fracture principles. Tissue damage is usually more substantial with higher velocity weapons (more than 610 m/s or 2000 ft/s) [4]; for example, injuries caused by modern military rifles and mine blasts. In modern local wars, more and more wounds are caused by splinters due to blast injuries (63.4%–73.5% of the injuries in the Afghanistan war, according to Nechaev et al. [99]). Wounding potential and lethality are related to the amount of kinetic energy that the projectile is able to impart to the target. Kinetic energy can be expressed by the formula: $KE = (m \cdot v^2)/2$, where m is mass and v is velocity.

Tissue damage is proportional but not equal to the amount of kinetic energy deposited in the target, calculated by subtracting the amount of kinetic energy of the bullet on exit from the amount of kinetic energy on impact with the body. Although a projectile's velocity and mass are inseparable, a greater mass results only in a linear increase in kinetic energy, whereas a change in velocity affects energy exponentially to the second power [5]. The bullet velocity is a major determining factor in the production of tissue damage [86]. The greater velocity leads to magnified energy absorption, which leads to increased tissue damage [35]. Commonly, gunshot wounds in civilians (low-velocity missiles) have more focal injury patterns and usually cause limited tissue damage from the missile injury alone, and not from cavitation effects [42, 59]. The majority of patients with low-velocity gunshot wounds may be safely and economically treated non-operatively with simple local wound care (superficial irrigation and careful dressing, with or without antibiotics) on an outpatient level, while associated limb fractures can be stabilized according to the principles in use for closed limb fractures, because of their similar characteristics (but see reservations below) [3, 5, 12, 59]. Modern military high-velocity missiles produce significant cavitations and fragments during their terminal ballistic phase. If the missile strikes bone, fragmentation of the bone, of the missile, or both may occur, and the resultant secondary missiles will produce additional tissue damage [34]. Gunshot wounds and blast injuries can cause either penetrating (not exiting) or perforating (exiting) wounds. The radiological appearance of a foreign body in the tissue of an injured limb is clear evidence that all the contained kinetic energy was expended in the missile–tissue interaction. Fragmentation of bullets has also been reported to correlate with higher missile velocity and delivered energy [36]. According to Gugala and Lindsey [42], the extent of bone comminution corresponds directly to the amount of missile energy transferred, and also suggests the degree of soft-tissue injury. In contrast, only some of the kinetic energy is absorbed by the tissues in perforating wounds where bullets fragments are not detected on radiography. Limited energy transfer by high-velocity missiles produces relatively less tissue damage and, in contrast, efficient transfer of energy by low-velocity missiles can result in devastating wounds [5]. Moreover, the impact energy of low-velocity shotguns at close range is similar to that of high-velocity firearms. Therefore, simply designating gunshot injuries as low-velocity or high-velocity wounds alone does not accurately reflect the true extent of the injury severity [42]. More appropriate and more important than velocity are the designations "low-energy" and "high-energy" which are more descriptive of the extent of tissue damage. Moreover, according to Long et al. [88], who studied the accuracy of classification systems for gunshot injuries in civilians, they do not provide a true description of the weapons because more than one-quarter of patients who suffered from firearm injuries cannot identify the weapon and, in many patients, the description is unreliable. He concluded that, in deciding upon treatment without knowing the type of weapon, the clinical and radiological appearance of the injured limb dictates the treatment protocol, and patients with extensive devitalized wounds must be treated according to the protocol for patients suffering from high-energy injuries.

The condition of the soft tissue of the injured limb is a vital factor, determining the chances of limb salvage procedures and the feasibility of functional restoration. In these fractures, the injuring agent transfers significant energy to the soft-tissue envelope, traumatizing these vulnerable structures and increasing the risk of major complications. Therefore, the initial care must be minimally traumatic and maximally sparing of the already damaged soft tissues. All fractures should be stabilized as early as possible. These patients are often polytraumatized and hypotensive, and may be hypothermic and coagulopathic. The use of a temporary external fixation device allows adequate resuscitation of the patient prior to definitive fixation [47]. High-energy trauma can include neurosurgical, general surgical, maxillofacial, ophthalmologic, otolaryngological, inhalation, burns, and other injuries. Rapid skeletal stabilization in patients with multiple complex fractures allows resuscitation with minimal blood loss and operative time [47], affording time for additional diagnostic imaging and adequate preoperative planning for the definitive elective limb reconstruction. The complexity and variability of these injuries dictate that routine prescriptive management based on fixed protocols is not possible and, therefore, a flexible and individualized approach to treatment is required [63].

Even in patients who suffer from closed fractures, soft-tissue injury plays a central role in prognosis and management. Because of the possibility of further soft-tissue damage caused by unstable fractures, the main bone fragments must be stabilized without delay. Stability is a very important factor, especially when there is a combined injury. Unstable fractures cause pain, nursing problems, morbidity, and mortality. Impaired bone healing results in delayed union or even nonunion. In contrast, early and sufficient fracture stabilization improves the recovery of the overlying soft tissues and the fracture itself. This is especially so in the treatment of patients suffering from war injuries, because the great forces involved result in extensive destruction of the bone and surrounding soft-tissue envelope. Classical fixation methods of fractures, such as plaster of Paris casting and continuous skeletal traction, are not acceptable in the treatment of patients suffering from high-energy unstable fractures with severely compromised soft tissues. Massive soft-tissue damage, extensive wounds (including post-fasciotomy wounds), and extensive post-traumatic fracture blisters require intensive daily soft-tissue care and preclude the use of cast immobilization. Furthermore, such severe fractures would require a relatively long period of immobilization, and this would result in stiffness in the neighboring joints. In addition, cast fixation cannot provide sufficient stability for early weight-bearing in patients with comminuted high-energy fractures, especially with bone loss. Skeletal traction, demanding lengthy immobilization, is unacceptable for treating patients with multiple and combined injuries, who require early mobilization and active nursing care.

Heavy contamination of the injured tissues precludes the use of internal fixation methods for fracture stabilization in these patients. Interlocking intramedullary fixation provides stabilization, achieved without additional periosteal damage, with secure control of alignment and rotation of bone fragments, wide access for soft-tissue care, early mobilization of the patient, and early movement of the adjacent joints. Interlocking nails have become the treatment of choice in the management of diaphyseal fractures of the long bones, including many types of open fractures. The disadvantages of this method are the potential spread of infection throughout the medullary canal along the nail, hardware failure due to the relatively small nail size, and technical difficulties in the treatment of distal and proximal one-third fractures. A study by Henley et al. [53] demonstrated a slight advantage of the unreamed interlocking intramedullary nail over unilateral 5.0-mm half-pin external fixators in the treatment of Gustilo Type II, IIA, and IIIB open fractures of the tibial shaft. However, patients with the most complex injuries, such as Gustilo Type IIIC fractures, tibial fractures caused by firearm projectiles, and fractures with significant bone loss, were excluded from this study, thereby significantly affecting its results.

Reamed interlocking intramedullary nails have a mechanical advantage over unreamed nails, but the reaming procedure of long tubular bones causes both mechanical and thermal damage to the medullary blood supply which cannot be tolerated when the injury has stripped much of the periosteal blood supply from the bone. According to Melcher et al. [94], reaming of the medullary cavity with the attendant reduction in local vascularity and necrosis may be additional risk factors.

The method of fracture stabilization utilizing a standard plating technique requires extensive tissue dissection. Exposure of the fracture site and bone fragments should be limited, in order to retain vascularization. A precondition for performing the plating procedure is the availability of immediate and reliable coverage of the fracture site and implanted internal fixator by viable soft tissues, and this condition is frequently absent in war injuries. The concept of "biological fixation" with new plate designs and minimized bone-plate contact, bridge-plating techniques, and improved surgical techniques with percutaneously inserted plates has led to improved rates of fracture union and a decreased incidence of infection and other postoperative complications. However, even the limited local pressure of plates on bone can damage the blood supply, essential for fracture healing, to the underlying bone [50]. Furthermore, an implanted internal fixator foreign body promotes infection in the wound in cases of septic complications. Even limited contact pressure plates require safe soft-tissue coverage without any compromise. Incisions through compromised tissue can lead to wound breakdown and deep infection [135]. Thus, methods of internal fixation using intramedullary nails or plating provide fracture stabilization at the cost of disturbing the intramedullary or periosteal blood supply [19]. Based on his experience in treating war injuries to the extremities, Busic et al. [16] reported a high rate of deep infection (33%) when internal fixation was used as the primary management. Hence, an internal fixator should not be used as a method of choice in the initial stages of treatment of war injuries. Long et al. [88] observed 100 patients who underwent surgical treatment for civilian gunshot injuries to the femur. They found that the femoral fractures of 79 patients with minimal soft-tissue damage united without infection, but 8 of 21 patients with severe soft-tissue damage had deep infection.

Fracture healing depends on an adequate blood supply and sufficient stability of fixation for a successful end result. The severity of the soft-tissue injury rather than the choice of implant appears to be the predominant factor influencing rapidity of bone healing and rate of injury site infection [53].

In treating poly-traumatized patients, external fixation provides a quick and minimally invasive approach. Using external fixation as a more biological method of skeletal stabilization helps preserve tissue vascularity. The advantages of this extra-focal method of fixation also include retention of the fracture hematoma without disturbing the soft-tissue envelope at the fracture site. Using external fixation frames in the management of these patients allows both quick stabilization and realignment of shattered bones, with minimal surgical invasion and additional disruption of the mangled soft tissue. The principle behind this method is stabilization of fracture fragments by the combination of transfixion of fracture fragments and an external stable framework distanced from the wound and capable of repeated adjustments [147]. There is no need for insertion of massive foreign bodies (internal fixators) into the fracture zone, demanding an appropriate surgical approach with additional incisions and soft-tissue trauma, in addition to adequate soft-tissue coverage of the bone ends, fracture zone, and implanted internal fixators. Care must be taken not to add further surgical devascularization of the bone ends. Thus, fracture stabilization is achieved without further compromising the already damaged soft-tissue envelope. External fixation frames allow simple and quick bone stabilization, provide simplicity in nursing care, and allow earlier mobilization of patients. The wounds are easily accessed and local treatments, including necessary surgical procedures, are readily applied. This versatile method of treatment may be employed in almost any configuration, severity, and localization of fracture. Reduction and stabilization of bone fragments should be performed with minimal trauma to the tissues, avoiding additional dissection, stripping and iatrogenic devascularization of the bone fragments (*primum non nocere*). Methods of external fixation, techniques using indirect fracture reduction, and procedures that obviate the need for direct exposure of the fracture site can avoid some of the complications associated with open reduction and internal fixation of bone fragments. According to Efimenko et al. [32], the introduction of functionally stable external osteosynthesis improves the results of treatment of gunshot limb fractures. External skeletal fixation is the preferred initial treatment for stabilizing severe open missile fractures of the limbs, reducing the rate of morbidity and limb amputations [47, 140].

Modern external fixation equipment is relatively easy to use and teach. It achieves quick, effective, primary fracture stabilization. These important properties are suited to operations, often executed under emergency conditions by duty teams of orthopedic residents, in the absence of highly skilled specialists in the field of limb salvage and reconstruction.

Temporary external fixation has been recommended to provide relative bone stability while the soft tissue heals, prior to formal open reduction and internal fixation. According to Haidukewych [47], using a protocol of temporary external fixation in complex peri-articular fractures will allow time to prepare the patient for surgery, prepare the surgeon for what needs to be done, and prepare the injured extremity for surgery. The use of temporary external fixation is an attractive strategy in the staged treatment of complex fractures.

External fixation devices provide several important advantages:

- Extra-focal fixation technique;
- Relatively easy application technique;
- Rapid and relatively stable fracture fixation using a minimal number of parts;
- Adequate fixation frame for any fracture configuration;
- Low morbidity, minimally invasive fixation technique;
- Temporary trans-articular bridging can be performed in patients with severe intra- and juxta-articular injuries.

The main disadvantages of external fixation are:

- Require daily pin-tract care;
- Discomfort;
- Local pin-tract infection rate;
- Sometimes interference with soft-tissue reconstruction;
- Muscle transfixion can result in neighboring joint stiffness;
- Need for prolonged on-going orthopedic follow-up in an outpatient clinic.

Primary Treatment

2

2.1 Primary Treatment and "Damage Control"

Patients who present with associated life-threatening injuries should be evaluated and resuscitated according to Advanced Trauma Life Support protocols. The initial care of a massively traumatized limb begins with the resuscitation of the patient, especially in patients suffering from multiple trauma. Surgical damage control includes an operative technique in which control of bleeding and stabilization of vital signs become the priority in saving the patient, together with prevention of contamination and protection from further injury. Severe multiple injuries can initiate a cascade of events resulting from blood loss and release of inflammatory mediators, leading to a "vicious cycle" of shock, hypothermia, acidosis, and coagulopathy, resulting in end-organ failure and death [51, 91]. Damage-control surgery is the most technically demanding and challenging surgery a trauma surgeon can perform. Many studies have reported that immediate stabilization of long bone fractures drastically reduced adult respiratory distress syndrome (ARDS), multiple organ failure (MOF), and sepsis – the effect of the "golden 24 h" [86]. The more severe the injury, the greater the effect of early fracture stabilization. Sufficient bone stabilization allows early mobilization from the bed, preventing severe complications, such as pneumonia and thromboembolic disease. The presence of major fractures increases the risk of MOF syndromes. This risk can be reduced by a comprehensive plan for early management, including operative fracture stabilization. However, the poly-trauma patient who survives the "first hit" from the trauma itself must be protected from the "second hit" phenomenon, i.e., the results of traumatic surgery.

Pape et al. [105] investigated the impact of intramedullary nailing as opposed to temporary external fixation for the treatment of femoral fractures in severely injured patients. In this study, an attempt was made to determine the operative burden by evaluating the perioperative concentrations of pro-inflammatory cytokines (interleukin-1, interleukin-6, and interleukin-8) in central venous blood. A significant and sustained inflammatory response was measured after intramedullary nailing performed within 24 h, but not after initial external fixation. These findings suggest that damage-control orthopedic surgery minimized the additional physiological impact induced by acute intramedullary fixation of the femur.

The concept of damage control orthopedics (DCO), relative to limb surgery in patients with severe multiple injuries, is an attempt to minimize the "second hit" of an emergency procedure of long bone stabilization, performed rapidly and atraumatically, and to release compartment syndromes. The principles of DCO are used to reduce the degree of surgical impact on patients with severe multiple injuries who are at risk for MOF. Vital for achieving this goal are minimizing the duration of initial surgery, avoiding additional blood loss, and performing only life- and limb-saving procedures [51] (Fig. 2.1.1).

2.2 Tissue Debridement

Often, the first surgical procedure determinates the long-term outcome of severe trauma. Major organ trauma may be present in patients suffering from high-energy, especially war, injuries. After stabilization of the patient's general condition, a thorough head-to-toe examination must be performed, checking the blood supply to the limbs, the neurological status of the limb, the bony stability, and the soft-tissue condition of injured extremities. Each wound should be evaluated completely and treated appropriately. It is essential to examine more than just the wound area; the entire extremity must be evaluated and radiographs of the adjacent joints must be obtained [5]. Radiographs of the fracture help determine the energy of the injury, although the soft-tissue damage is usually greater than what is visually evident [144]. Tetanus prophylaxis should be administered immediately, based on the patient's immunization status. Intravenous antibiotic combination therapy [115] using a first-generation cephalosporin (cefazolin 1.0 g t.i.d.) active against Gram-positive organisms, and an aminoglycoside (gentamicin 240 mg/day), active against Gram-negative organisms, is started in the emergency room

Fig. 2.1.1a–c. Primary external skeletal stabilization used in emergency treatment of complex poly-trauma patients

for patients suffering from open combat trauma and is continued for 3 days. Penicillin 5,000,000 units q.i.d. should be added to the antibiotic regimen when conditions favoring the development of anaerobic infections exist (soil contamination and vascular injuries). As soon as the patient is hemodynamically stable, he or she must be taken to the operating room.

The major factor determining the outcome in high-energy injuries to the limbs is the severity of the soft-tissue injury. Open fractures communicate with the outside environment and the resulting contamination of the wound with microorganisms, coupled with the compromised vascular supply to the region, leads to an increased risk of infection as well as to complications in healing [146]. Primary radical debridement is a crucial phase in the management of patients after open high-energy injuries. Aggressive extensive debridement of all damaged tissue surrounding the bullet tract from high-velocity military weapons has been standard military surgical practice. Inadequate debridement remains the major cause of chronic infection after severe extremity trauma [130]. In 2003, Bartlett wrote: "The evaluation and treatment of damaged muscle remains one of the surgeon's greatest challenges" [4]. Inadequate debridement of open fractures is often the rule rather than the exception, because tissue devitalization is usually not appreciated immediately [22, 45, 108, 129]. Inadequate excision of missile wounds of the extremities will leave necrotic tissue in the wound, predisposing to infection and to possible later amputation [148]. No principle is more important in the care of an open fracture than copious irrigation and meticulous wound debridement [141]. Before the patient is anesthetized, a thorough neurological examination of the injured limb should be conducted, unless the patient is unconscious, or a proximally placed tourniquet is in place, creating limb numbness.

General anesthesia is the "gold standard" for the treatment of patients suffering from multiple fractures to the limbs. Spinal or regional anesthesia can be useful tools for treating patients with isolated damage to the limbs.

Thorough and copious irrigation of contaminated wounds will lower the risk of infection [102]. However, there is no consensus regarding optimal volume, pressure, or the desirable additives to the irrigation fluid [59]. According to a study performed by Draeger and Dahners [29], suction and sharp debridement, as practiced by most surgeons, may remove foreign bodies well without the use of high-pressure pulsatile lavage (HPPL). Moreover, HPPL may drive some contaminants deeper into tissue already compromised by trauma, rather than remove them. Furthermore, this study supports the conclusion that pulsatile lavage rather than low-pressure irrigation methods, including bulb syringe and suction irrigation, may further damage soft tissues.

In performing a primary debridement procedure, the involved limb is prepared circumferentially and draped free so as to leave all important skeletal landmarks visible. A tourniquet is applied to the proximal part of the extremity, to be used only when necessary (active bleeding); otherwise, the debridement procedure is completed without inflating the tourniquet. This prevents additional ischemic damage to already severely traumatized tissues during the operative procedure. In addition, there may have been a prolonged tourniquet time from the injury event until hospital admission. Even when a tourniquet is obligatory, the tourniquet time should be kept to a minimum, since using a tourniquet in treating lower extremity trauma has been shown to increase the incidence of wound infection, presumably by increasing tissue hypoxia and acidosis [112].

Generally, the operation is performed with repeated and thorough washing of the post-traumatic wound and skin on all surfaces of the injured extremity with chlorhexidine soapy scrub followed by normal saline and/or Ringer's solution. An additional flushing with hydrogen peroxide solution is recommended. All visible and palpated foreign bodies must be removed from the wound. All devitalized soft tissues in the wound bed must be removed. The denuded and comminuted bone fragments with questionable viability must also be removed. Wounds are surgically extended into the adjacent "normal" tissues along the lines of described surgical exposure to allow for complete visualization and adequate exposure of the tissues in the trauma zone. Primary surgical debridement of the wound must be radical and aggressive, with excision of all devitalized tissues which can be a source of tissue necrosis and infection in the future. Excision of the wound skin edges not only removes devitalized tissues but also improves the exposure of the depth of the wound.

The borders of the damaged tissue area with the normal tissues in cases of high-energy trauma are usually contused and can not be precisely distinguished. The classic symptoms of the "four Cs" – color, consistency, contractility, and the capacity to bleed continuously – must be checked and detected during surgical debridement of muscle [4]. When the borders have been defined, all non-viable skin, subcutaneous fat, and muscle should be removed sharply. All intact segmental muscular vascular branches must be preserved to avert further local muscle ischemia. All non-viable tissue must be removed, while as much functional tissue of the tendons, joint capsule, and ligaments as possible is spared during extensive debridement unless it is extremely contaminated or macerated (Fig. 2.2.1).

Debridement of non-viable soft tissue and irrigation with normal saline are repeated during the operative procedure. All denuded bone fragments must be removed from the wound, avoiding devascularization of the fracture zone. According to Brusov et al. [14], a 5- to 5.5-cm degloving of the periosteum from the bone ends can be detected in most cases of high-energy trauma. Bony debridement is controversial, with recommendations varying from replacing large free contaminated cortical fragments to removing cortical bone until bleeding from the edges is seen [92]. The fragments are most often saved to add to the mechanical integrity of internal fixation. According to McAndrew and Lantz [92], deep wound infection occurred in 7%–25% of patients in whom devascularized cortical fragments were saved, and these failures were commonly due to inadequate bone debridement. The various possibilities of the Ilizarov method in providing stable fixation in patients with severe bone comminuting, even in cases of extensive post-traumatic bone loss, and the potential bridging of bone defects using distraction osteogenesis, allows for radicalism during primary surgical debridement. This reduces the quantity of non-vital tissues in the wound, thus diminishing the risk of wound deterio-

Fig. 2.2.1a–f. A 19-year-old male. Injury secondary to mine explosion affecting the right tibia. **a** Large crush wound on lateral aspect of proximal leg (before debridement). **b** Primary debridement with excision of necrotic and non-bleeding tissue was performed. Anatomical intact deep peroneal nerve was found. **c–f** Clinical pictures at the 12-months follow-up demonstrate wound healing with full range of movement of the ankle joint *(continues on next page)*

Fig. 2.2.1a–f. *(continued)* **c–f** Clinical pictures at the 12-months follow-up demonstrate wound healing with full range of movement of the ankle joint

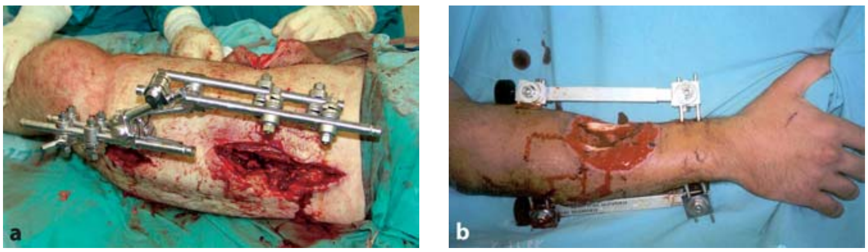

Fig. 2.2.2a,b. Clinical pictures of patients suffering from open high-energy limb fractures. An emergency procedure is carried out with stabilization of fractures with tubular AO (**a**) and Wagner (**b**) external fixators. The wounds are left open

ration and avoiding multiple surgical procedures in the future (Fig. 2.2.2).

For patients with vascular injuries (Gustilo IIIC fractures) or when open crush injury is significant, prophylactic fasciotomies must be performed. Compartment syndrome may occur in massively traumatized limbs and must be considered as a cause of limb ischemia. Swelling of muscle fibers to as much as 5 times normal size can be observed, and local edema may lead to compartment syndrome with further increase to the soft-tissue insult [35]. An open fracture does not automatically relieve the compartment of the injured limb, and even these patients can go on to develop compartment syndrome. Fasciotomy must be performed if any question of compartment syndrome exists. According to Moed and Fakhouri [96], prophylactic fasciotomy is indicated if there is the slightest indication that compartment syndrome will occur (Fig. 2.2.3).

If the wound is heavily contaminated and the soft-tissue damage is extensive, it is difficult to judge the extent of tissue excision. When finishing primary debridement procedures in patients suffering from high-energy injuries, primary closure of wounds must be avoided because of the contamination and retention of necrotic tissues. The widely accepted standard of care of soft-tissue injuries associated with open fractures is to leave the traumatic wound open after the initial surgical debridement [141].

During primary inspection and debridement of the wound, it is usually not possible to precisely assess the level and extent of the tissue damage and, as a general rule, meticulous repeated surgical debridements are required to achieve the best possible infection control. Repeated serial debridements are required for patients with high-velocity war injuries, especially those suffering from blast and crush injuries. A second-look procedure and repeated surgical debridement is to be performed under general anesthesia at 36- to 48-h intervals. This serial inspection under anesthesia and debridement of necrotic tissue should be undertaken until final closure is deemed to be safe (Fig. 2.2.4).

2.3 Vascular Injuries

Injuries with concomitant damage to the major extremity vessels require special consideration. Fox et al. [38] reported a high percentage of vascular injuries to the extremities in battle trauma. Life-threatening traumas to the head, chest, abdomen, and pelvis deserve priority, but delay in dealing with limb vessel trauma may be reflected in an adverse outcome. A high degree of

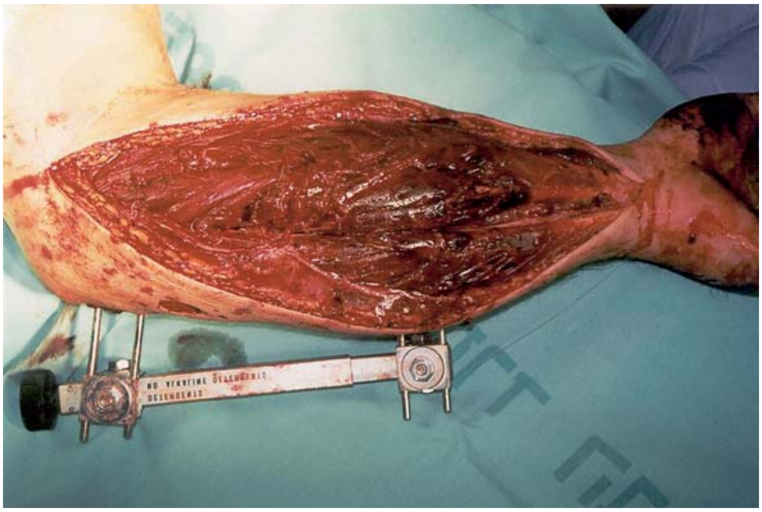

Fig. 2.2.3. A 33-year-old male with crush injury to the left forearm. Immediate fasciotomy was performed to handle acute compartment syndrome. The ulnar bone fracture is stabilized using a Wagner external fixation frame

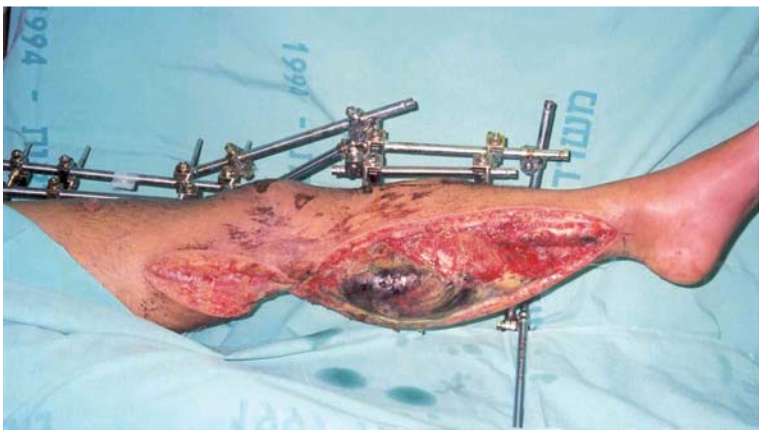

Fig. 2.2.4. Third day after severe motorcycle injury. Poor local condition with necrotic tissues dictates repeated surgical debridement

suspicion of vascular injury in high-energy trauma is mandatory, especially in peri-articular knee and elbow localizations, when treating fractures with gross displacement, and in patients with primary neurological deficits. Indications for immediate vascular surgery in such conditions are usually determined by a physical examination with special attention to pain, bleeding, pulsating masses, expanding hematomas, color of distal part of the extremity, paresthesia (or anesthesia), paralysis, and capillary refill time (signs of acute ischemia). A Doppler scan can be performed immediately in the emergency room or operating theatre. Angiographies or computer tomography are not usually useful in patients suffering from massive bleeding, and/or in a severe general condition, or in mass casualty situations [98]. Preoperative angiography and a CT-angio examination can be useful tools in patients in stable general and local conditions and when there is a high suspicion of vascular injury to the limb, providing they do not endanger the limb by extending the ischemia time beyond permissible limits (Fig. 2.3.1).

Vascular repair must be performed as soon as possible. Surgical reconstruction in the "golden interval" – up to 4 h after injury – provides better functional results. The possibility of simultaneous damage to different vessels and damage to the same vessel at different anatomical levels must be suspected in the treatment of patients suffering from blast or shrapnel injuries. The ends of the injured vessels must be debrided and anastomosed. If an end-to-end suture is not possible, a reversed autogenous saphenous vein graft is the best alternative [95, 129]. According to Fox et al. [38], management of arterial repair with autologous vein graft remains the treatment of choice.

Immediate stable osteosynthesis is necessary to prevent thrombosis and occlusion, secondary damage

Fig. 2.3.1. Angiography of the right leg in a patient suffering from blast injury demonstrates occlusion of the anterior tibialis artery. Note radiological signs of foreign bodies above projection of ankle joint

to vascular anastomoses, and bleeding after vascular reconstruction. In the treatment of fractures with concomitant vascular injuries within the 4-h ischemia limit, we use the following surgical tactics:

- copious lavage of the wound and initial debridement;
- skeletal stabilization of the fracture using simple unilateral external fixation frame (assembly takes usually 20–30 min);
- further debridement;
- vascular reconstruction.

Thereby, we provide the necessary conditions for vascular repair: stability during vascular surgery and prevention of further damage to repaired vessels. Moreover, it is possible to fix the injured segment of the limb with shortening or angulation, releasing the site of the vascular repair from tension forces, especially in the treatment of patients suffering from blast or crush injuries with extensive tissue damage.

When more than 4 h has passed and limb ischemia is present, vascular reconstruction has priority over skeletal immobilization [98]. The time from injury to reperfusion can be shortened using a temporary intraluminal vascular bypass shunt, connected to both ends of the artery to reestablish arterial flow; establishment of blood flow to the distal extremity is achieved prior to stabilization. A simple unilateral external fixation frame must be applied, providing prompt fracture stabilization to protect the site of the vascular repair and offering adequate access to the wound for debridement and subsequent soft-tissue surgery, including final vascular reconstruction. This provides the vascular surgeon with a stable operative field. In addition, the temporary vascular shunt will facilitate the manipulation of the bone fragments in performing reduction and surgical stabilization. Now, having achieved a condition of bone stabilization, it is possible to perform definitive vascular reconstruction (Fig. 2.3.2).

The possibility of thrombosis of the repaired vessel dictates the desirability of surgical reconstruction of all the main injured vessels, if possible, in patients with multiple vascular damage in any limb segment (Fig. 2.3.3).

Prophylactic fasciotomy is necessary in reperfusion after vascular damage, compartment syndrome or distal limb ischemia. The leg is the most common site for the development of compartment syndrome of the lower limbs. The standard two-incision medial and lateral approach is by far the simplest and most effective method for decompressing all four compartments (Fig. 2.3.4, Fig. 2.3.5).

2.4 Peripheral Nerve Injury

According to Hopkinson and Marshall [56], small blood vessels are prone to rupture, while larger arteries are relatively resistant to injury (unless directly struck). Similarly, large nerve trunks are also rarely completely disrupted, while being susceptible to neurapraxia [57]. Most peripheral neurological injuries are neurapraxic and spontaneous recovery occurs frequently without exploration or repair of the nerve [13, 66]. According to Karas et al. [60], the majority of the nerve injuries sustained during gunshot wounds to the upper extremity are traction injuries. In unconscious or drugged patients and in patients with tourniquets, neurological diagnosis on admission may be very difficult. As soon as the casualty is able to cooperate, a rapid neurological examination must be done and recorded, starting at the medical aid station echelon [107]. The examination consists of asking the patent to gently move the limbs at all joints in all directions, as much as the wounds allow, and rapidly checking the limbs for loss of light touch.

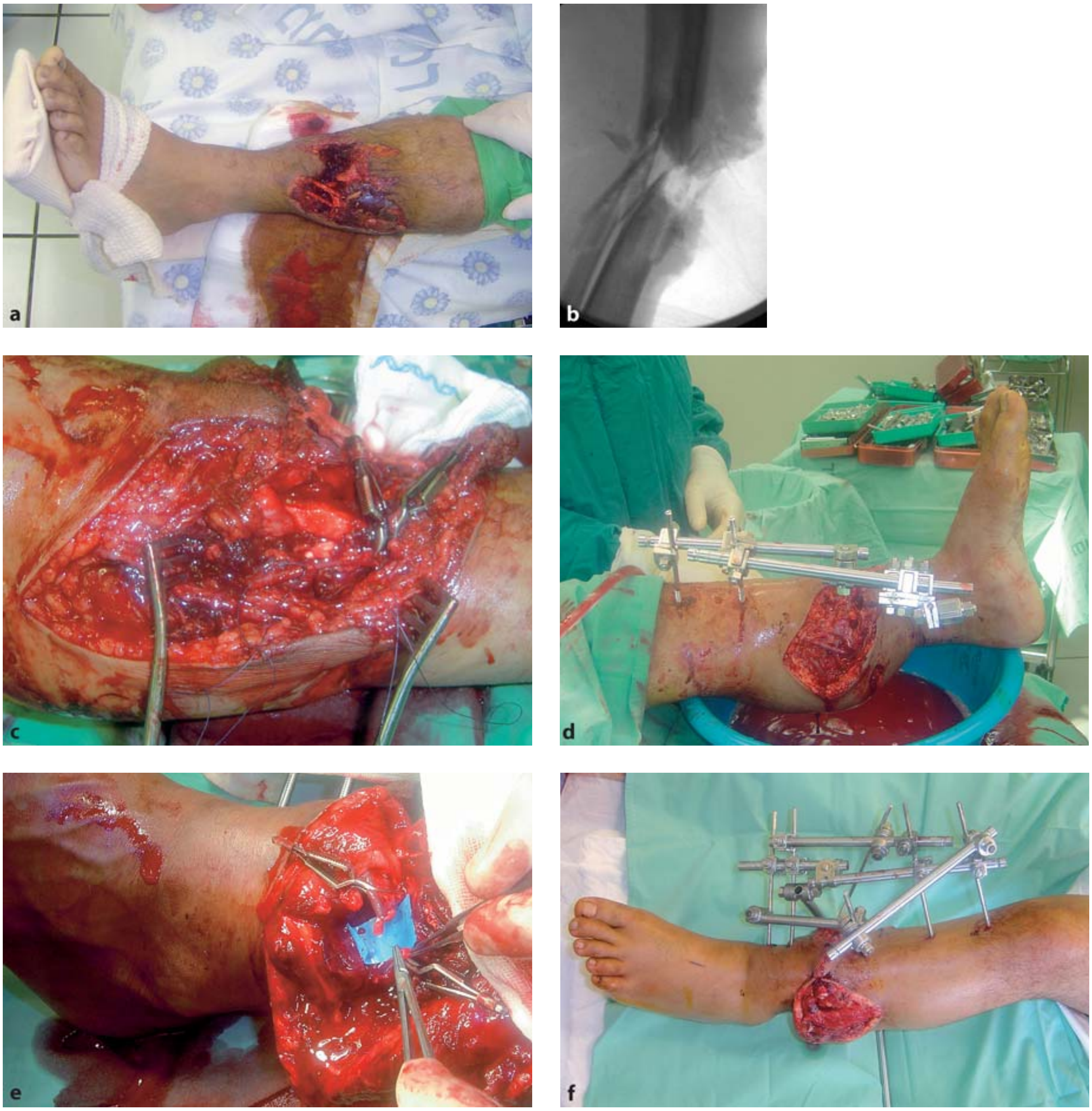

Fig. 2.3.2a–f. A 26-year-old male. Open Gustilo–Anderson type 3C tibial fracture with bone and soft-tissue loss secondary to blast injury. **a** Clinical picture on admission (6 h after injury). **b** Radiograph on admission demonstrates a comminuted fracture of tibial and fibular bones with bone loss. **c** Distal limb perfusion is restored using temporary intraluminal vascular bypass shunt to the tibialis anterior artery. **d** Primary stabilization of the tibial fracture with tubular external fixator is performed with shortening. **e** Clinical picture performed during final vascular reconstruction by end-to-end suture. **f** Final augmentation of the tubular external fixation frame is performed

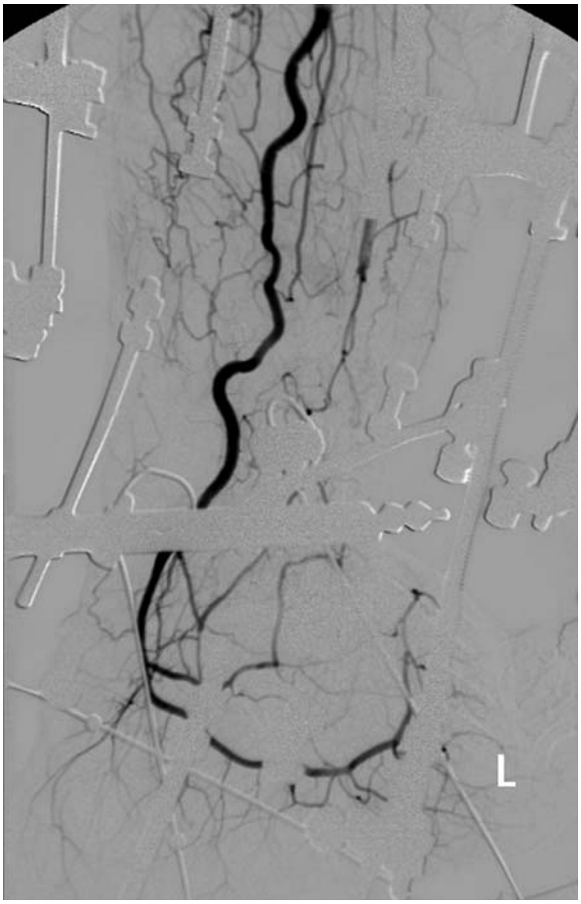

Fig. 2.3.3. Angiography performed on the third day after primary vascular reconstruction of anterior and posterior tibial arteries demonstrates thrombosis of anterior tibial artery

These findings should be interpreted in the light of knowledge of peripheral nerve anatomy and the site of penetrating or closed injuries. Electrodiagnostic studies are usually not helpful on admission and in the early post-injury period in seeking neural injuries, because they cannot distinguish between a neurapraxis lesion and a more serious injury [5]. Dynamic splints must be used in treating patients with post-traumatic peripheral nerve injuries since, in the early stage of management, avoiding pressure over anesthetic or hypoesthetic areas must be the rule. Daily gentle passive movements can help in preventing joint stiffness. Accordingly to Omer [103], 70% recovery of patients with peripheral nerve gunshot injuries to the upper extremities was observed, the majority of gains occurring over 3–6 months (average, 3–9 months). Brien et al. [13] reported that 60% of patients with peripheral nerve gunshot injuries to the lower extremities (sciatic and peroneal nerve) regained some degree of nerve function. According to Deitch and Grimes [26], the potential for long-term nerve injury is highest in patients with high-velocity injuries and blasts, and they are also more often complicated by chronic pain and reflex sympathetic dystrophy. In 2003, Bartlett [4] concluded that acute repair seems to be rarely indicated for isolated gunshot nerve injuries to the extremities. When debriding a severe wound in the vicinity of a major nerve whose function is in doubt, the nerve should be explored without causing more soft-tissue damage in both proximal and distal directions from the contused area, until the appearance of the nerve is normal. Conditions are usually not good for primary or delayed primary nerve repair [107]. Nerve exploration is indicated, if a vascular injury is to be explored, after a negative change in neurological status after closed reduction and no clinically or electromyographically documented nerve function 3–6 months after injury [113, 145], or when a neurotmesis was observed and marked during wound debridement.

2.5 Primary Skeletal Stabilization

Unilateral external fixation quickly became established as a rapid, efficient, and relatively simple method of fracture stabilization, permitting vascular repair and control of the wound, retaining the distance between bone fragments and preventing contracture of the muscles, allowing mobilization of the limbs and facilitating evacuation, all of which are considerable advantages in the acute trauma setting [68]. The ease of mounting the unilateral external fixator is also a great advantage. Thus, we usually prefer unilateral external fixation frames for primary fracture stabilization.

After finishing the primary debridement procedure, all surgical instruments used for excision, drapes, and surgical gloves must be changed. The injured limb must be re-prepared and re-draped. The whole operated limb must be draped free: first, there must be continuous visual control of the color of the distal parts of the injured limb (including fingers or toes), capillary filling, and the possibility to palpate the peripheral arterial pulses. Second, severe and unusual trauma situations may dictate unorthodox approaches for the insertion of fixation elements from any direction. Third, adjoining joints must be seen during surgery to avoid unsuspected malpositioning (usually malrotation) of the bone fragments during the fixation procedure. Fourth, the possibility of extending an external fixation frame across adjoining joints with necessary temporary trans-articular bridging dictates a need to keep the operated limb fully exposed in these complex surgical situations (Fig. 2.5.1).

Prior to a half-pin insertion procedure, major vessels, nerves, musculo-tendinous units, large bone fragments, and pertinent skeletal landmarks should be marked on the skin. *The non-anatomical localization of important structures due to severe displacement of bone ends must be kept in mind!*

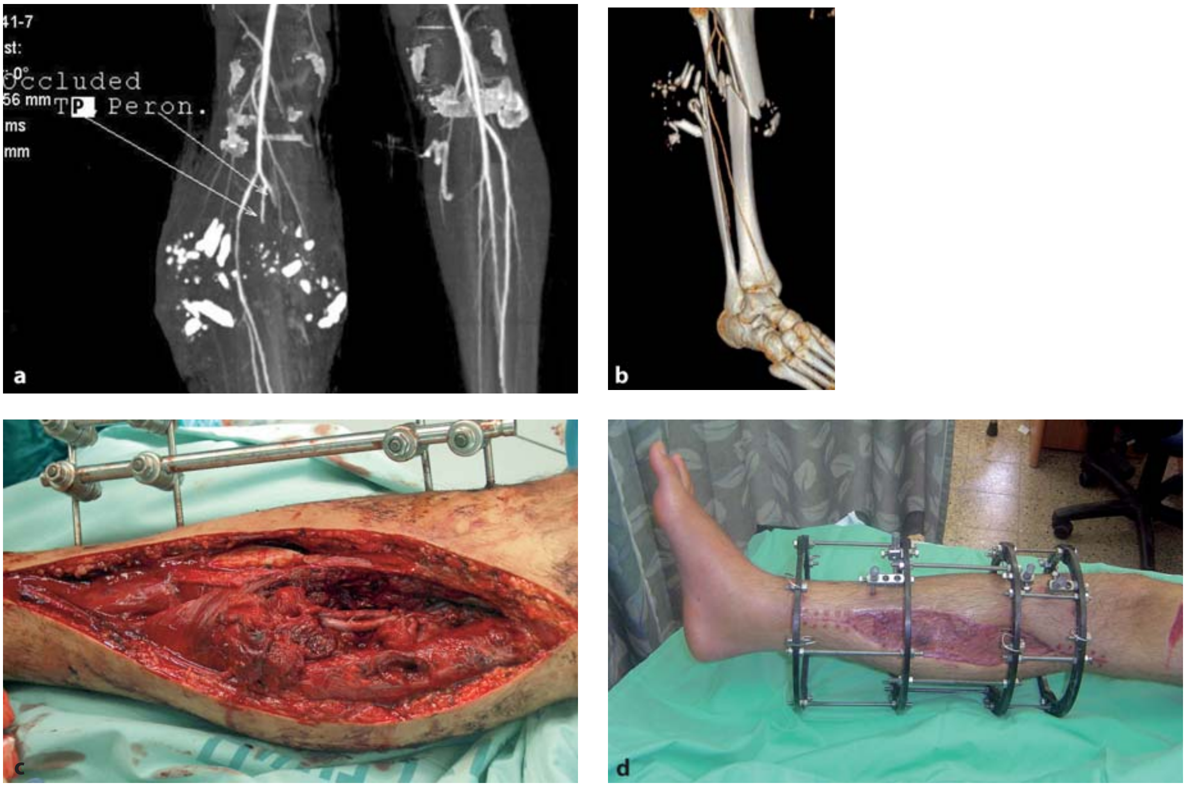

Fig. 2.3.4a–d. A 20-year-old male. Open Gustilo–Anderson type 3C tibial fracture secondary to anti-tank rocket blast injury. **a**,**b** CT-angio examination on admission demonstrates damage of posterior tibial and peroneal arteries of the right leg. **c** Primary debridement, fasciotomy, stabilization with tubular external fixator, and reconstruction of the posterior tibial artery and vein using a venous autograft was performed immediately. Clinical photo before partial closure of the wound for coverage of the vascular anastomoses site. **d** Follow-up 2 months after injury. Clinical photo demonstrates closure of soft-tissue defect by skin graft. Fixation of the tibial fracture by circular Ilizarov device

Fig. 2.3.5. A 23-year old male. Open Gustilo–Anderson type IIIC distal femoral fracture secondary to grenade blast injury. Primary debridement, fasciotomy, partial closure of exposed fracture site, and trans-knee stabilization with tubular external fixator were performed immediately

Fig. 2.5.1a,b. **a** Clinical appearance of intra-operatively missed malrotation of the humeral bone resulting from primary external fixation for an open humeral shaft fracture in a multi-injured patient. Orientation by means of the radiological image alone, but not by observing the clinical rotational malalignment, was the cause of this mistake. Note extensive internal malrotation of the upper limb. **b** This malrotation was repaired in a closed manner 3 weeks later, with conversion of the unilateral external fixator to the Ilizarov circular fixation frame

Unilateral tubular external fixation frames are usually used for primary fixation of bone fragments in treating patients with severe complex high-energy fractures with gross contamination. Unilateral external fixation devices with half-pins have a number of substantial advantages in the treatment of acute trauma, such as relative simplicity in assembling the frames and fixing the fracture, and have quickly established themselves as a quicker and easier method of primary fracture treatment than other methods of external fixation, especially in treating poly-traumatized patients. In our experience and in the current literature, the average time required to place a tubular external fixator is 20–30 min [68, 122]. This is a very important factor in the management of poly-traumatized patients and in mass casualty conditions. This frame configuration is stiff enough to maintain alignment under adverse loading situations, and is modular and sufficient for a wide variety of injuries. The unilateral configuration of the fixation device and the one-site technique for insertion of half-pins to the bone minimize the risk of iatrogenic soft-tissue damage, possible injury to the main vessels and nerves, and "trans-fixation" of the musculo-tendinous units, especially in treating proximal femoral and humeral bone fractures. The assembled unilateral fixation device allows the performing of initial debridement and secondary procedures on the soft tissues without removing the fixation frame. Many different external fixation systems for almost every bone in the body have been developed: AO, Hoffmann, Orthofix, Dinafix, EBI-fixators, etc. *Generally, use any type of frame you are trained to use, providing that it is quick and simple to apply.*

Our fixator of choice for primary stabilization is the AO (Synthes AG, Chur, Switzerland) tubular external fixator in a one-plane unilateral configuration. It is very simple and easy to learn, practical to use, and stiff and modular enough to accommodate a wide variety of situations [6]. A minimal number of different parts of the set allows a wide variety of frame assemblies. Usually, a pair of 5- to 6-mm threaded half-pins is introduced to both main bone fragments (proximal and distal). We prefer 6-mm half-pins due to greater bending stiffness and accordingly greater stability of the fracture fixation. For most femoral fractures, the half-pins are positioned at the lateral thigh, but for tibial fractures they may be placed either anteromedially or anterolaterally. To minimize post-fixation restriction of motion in adjacent joints, the half-pins must be inserted into the bone in functionally neutral zones and also in places with the least soft-tissue thickness. Each patient, especially after high-energy trauma with severe soft-tissue damage, needs an individual approach in choosing the right place for insertion of the half-pins. The better the condition of the skin and soft tissues at the insertion site, the less the possibility of developing local pin-related complications during the treatment period. If necessary, and if other appropriate sites for the insertion are absent, emergency temporary fracture stabilization can be performed by introducing the Schanz screw even to the uncovered bone. As soon as possible thereafter, this site must be covered by a soft-tissue flap, or the Schanz screw must be changed to another in a more acceptable location. The half-pin location must be planned to avoid disturbance of the nearby soft-tissue reconstructive procedures. A Kirschner wire, used as a probe, can help to determine the position of displaced bone fragments and to find the right sites for screw insertion. The widely recommended technique of low-speed and fractional drilling for half-pin insertion into the bone must be followed to avoid thermal damage to the hard and soft tissues. In addition, after performing an approximately 1-cm longitudinal skin incision, a triple trocar, including drill sleeve, must be used for bone drilling and also for introducing the half-pin to the bone to protect the surrounding soft tissues from thermal damage and from becoming twisted around the revolving instruments. The trocar must be centered on the bone before the drilling procedure. We recommend pre-drilling in the near and far cortex, because self-drilling half-pins, especially in the hands of insufficiently trained surgeons with relatively limited practical experience, can be dangerous for the surrounding soft tissues. The Schanz screws must be inserted across both cortices. Insertion of conical 6-mm half-pins into the bone must be accompanied by radiological control, because attempting to pull back a half-pin inserted too deeply results in significant diminution of the steadiness of the half-pin in the bone. The use of multi-directional half-pins can significantly increase the stability of the frame (Fig. 2.5.2).

A wide base of fixation (long lever arm) on each of the main bone fragments is desirable for improving stability of fixation. Insertion of half-pins into bone fragments close to the fracture zone must be performed at a distance of 4–5 cm from the ends of the bone fragments. The most proximal and distal half-pins are introduced into the bone near the metaphyseal zone (Fig. 2.5.3).

The wider the base of the external fixation frame, the more stable the fixation, the less the danger of pin loosening and local pin-tract infection, and the less the loss of reduction of the bone fragments. In addition, the wide base of the bone fragment fixation facilitates the management of bone fragments during the fracture reduction procedure. When dealing with short distal or proximal tibial or distal femoral fragments, it is desirable to fix with three half-pins, with two of them inserted into the metaphyseal zone at the same level (Delta frame). *Keep in mind localization of musculotendinous units and collateral ligaments to preserve the range of early post-operative motions* (Fig. 2.5.4).

Increasing the diameter of the half-pins and their number in each of the fragments of fixed bone greatly helps fixation stability. In treating large and obese patients with oblique fractures or severely comminuted bones and for the stabilization of femoral bone fractures, it is desirable to introduce three half-pins into the proximal and distal main fragments. Initially, the outer ends of the Schanz screws in each main bony fragment are connected by two short longitudinal tubes. Each of these proximal and distal blocks is then connected using tube–tube clamps to two intermediate connecting tubes. Manual reduction is stabilized by tightening tube–tube clamps on to connecting tubes. *Keep the rotational alignment in mind!* Reducing the distance between the bone and the longitudinal tube is important for increasing the stiffness of the frame. In peri-articular and intra-articular fractures, osteo-ligamentous injuries, severe intra-articular penetrating injuries, and damage to the capsule and ligamentary complex of joints adjoining the fracture site, there is a need for temporary trans-articular bridging of the injured limbs. In addition, this fixation is an effective tool for increasing stability in patients with fractures with a very short para-articular fragment. Technically, such fixation can be achieved by inserting two or three additional half-pins to the bony diaphysis 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 device, thereby stabilizing the fracture. Two tubes are enough for such a trans-articular crossing. Such a construction, although appearing outwardly to be massive, has relatively little weight and allows early patient mobilization, significantly easing nursing problems (Fig. 2.5.5, Fig. 2.5.6).

For the management of complex fractures of the upper limbs and performing primary surgical fixation of the relatively small forearm and hand bones, the use of small external fixators with 2.7- and 3.5-mm special Schanz screws is indicated. The rules and principles for using small external fixators are the same as for standard external fixation frames, including Delta configurations for temporary trans-articular bridging. These small external fixator configurations may be applied also to stabilize the small bones of the feet in treating complex trauma to the lower limbs. Additional percutaneous thin wire fixation may be required to optimize alignment and effect bone stabilization [55] (Fig. 2.5.7, Fig. 2.5.8).

Elimination of bone fragment displacement and anatomical reduction of the fractures at the stage of primary surgical debridement prevent pressure on the soft tissues and help uncomplicated wound healing. The fracture reduction procedure, performed in the acute phase of treatment, presents no significant technical difficulties, especially in open wound conditions in which the fracture zone and the bone fragments are exposed, resulting in a technically relatively easy open fracture reduction under vision. There is no significant resistance of the damaged soft tissues when performing the operative procedure in the acute period, because of the temporary post-traumatic paralysis of the muscles of the limb segment, which frequently exists. Furthermore, there is no stiffness in the neighboring joints. Thus it is desirable and possible even in the early stage of treatment to achieve the most precise anatomical reduction of the bone fragments. Great care must be taken to secure proper rotational alignment of the bone fragments before tightening the clamps. Accurate positioning of the bone fragments in the primary fixation frame is desirable, especially when taking into account that conversion to the final skeletal fixation may be delayed or even impossible in some patients due to a complex general