

Lower Limb Salvage: Indication and Decision Making for Replantation, Revascularisation and Amputation

Zachování dolní končetiny: indikace a rozhodování o replantaci, revaskularizaci a amputaci

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SUMMARY

Defining reproducible criteria for lower extremity salvage following severe high-energy trauma continues to be one of the most challenging and controversially discussed fields in orthopaedic surgery. At present, however, the difficult performance, limited availability and number of valid reconstructive options for complex injury types, i. e. simultaneous osteoligamentous trauma with neurovascular lesions and severe soft tissue defects (*“composite/compound multilayer defects”*) represent the decisive prognostic injury components triggering and determining the fate of the limb. Consequently, due to the complex injury pattern of the extremity and the overall situation of multiple injured patient the treatment and decision making has to be made in a priority-adapted algorithm. In this treatment algorithm interdisciplinary cooperation with vascular and plastic surgeons is of tremendous importance. Although the number of severely injured patients remains stable in the last decade, changes in the treatment algorithms result from increased survival rates of multiple injured patients and improved modern reconstructive options leading to continuously increasing rates of salvaged limbs. This paper aimed to systematically review the current literature for lower extremity injuries in order to unravel the different surgical treatment options and provide guidelines for decision making with corresponding treatment algorithms for limb salvage. Furthermore, the experiences in the management of mangled extremities in our centre are presented and illustrated/underscored with different cases.

INTRODUCTION

Defining reproducible criteria for lower extremity salvage following severe high-energy trauma continues to be one of the most challenging and controversially discussed fields in orthopaedic surgery. Due to advances in reconstructive techniques of skeletal, vascular and soft tissue injuries of the past two decades the rate of salvaged lower limbs has stepwisely increased, restricting primary amputation only to selected cases (<10% of all grade IIIB/C open lower limb fractures) (9, 20, 24). Among other factors, improved surgical methods aimed to preserve bone viability using minimal invasive, percutaneous techniques with interlocking nails, angular stable plates and/or hybrid Ilizarov constructs have in combination with options for secondary free or vascularized bone transfer, growth factor administration- largely resolved the “bone problem”. However, in complex injury types, i. e. simultaneous osteoligamentous trauma with neurovascular lesions and severe soft tissue defects (“*composite/compound multilayer defects*”) the degree and severity of soft tissue injury represent the decisive prognostic injury

components, triggering and determining the fate of the limb (28, 35, 58). Nevertheless, constant improvement and refinement of these osteosynthetic and microsurgical measures have decreased residual non-union rates following IIIB/C open fractures to nearly 20% (6). At present, however, the difficult performance and limited nation-wide/local availability of necessary infrastructural and staff preconditions that are required to perform advanced techniques are the major causes for a significant rate of patients suffering from impaired outcome. Due to missing registers, precise ablation rates of European countries cannot be exactly assessed. Owings et al. have reported amputation rates for the United States with approximately 185.000 amputations performed annually, while 16% are related to severe trauma (44). Despite this relatively low trauma-related amputation rate, lower limb loss due to severe injury accounts for 45% of the estimated 1.6 million people living with an lower limb amputation in the United States (66). This possibly reflects the fact that mostly young people suffer from an amputation due to trauma. Notably, severe lower extremity trauma is associated with additional musculoskeletal injuries in nearly 50%.

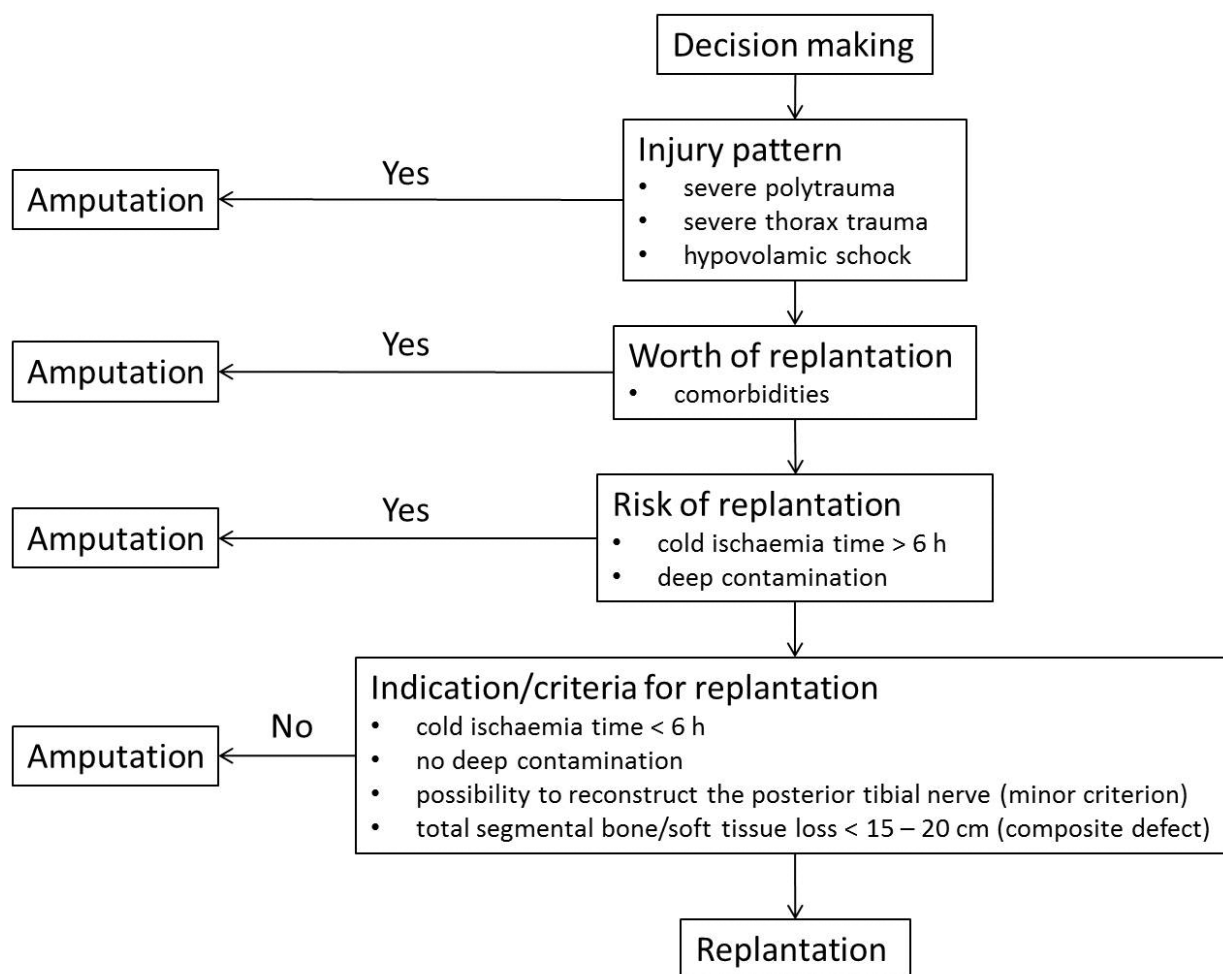


Fig. 1. The decision making process has to consider multiple intrinsic and extrinsic patient factors. Therefore a stepwise approach is recommended in order to increase rate of successfully replanted lower limbs.

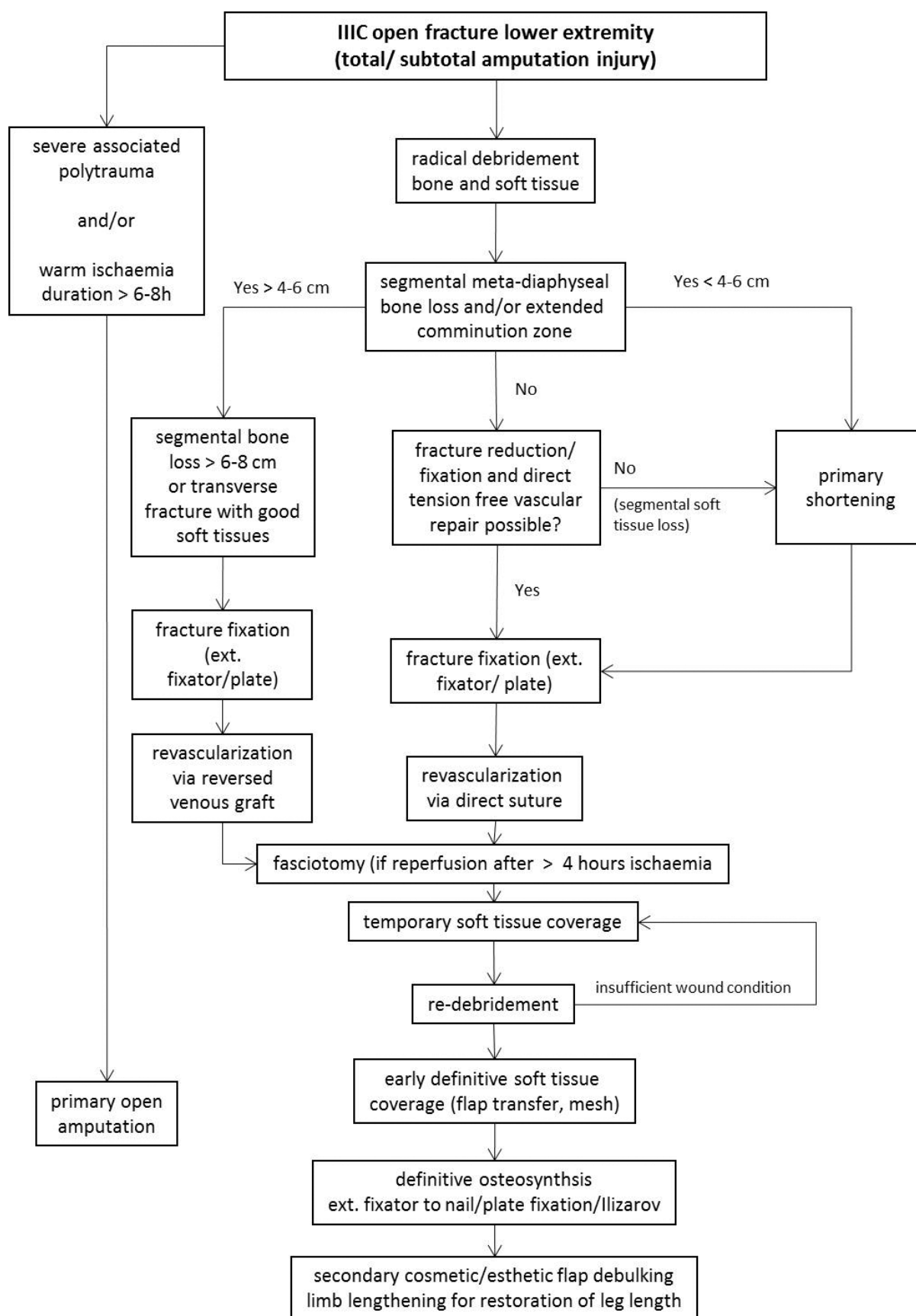


Fig. 2. The treatment algorithm follows a detailed concept once the decision for replantation is made. This algorithm shows the staged approach for vascular, bone and soft tissue reconstruction.

In view of the functional outcome, quality of life, duration/number of hospital stays many studies are published with partly inconsistent results. While some investigators have found functional outcome following reconstruction to be inferior when compared to those observed after early amputation and good prosthetic supply others report the opposite (13, 16, 19, 22, 28). However, most of these studies have a retrospective design with heterogeneous injury patterns and small patient numbers (19, 20, 22, 24). The largest and most popular recent multicentre study is the lower extremity assessment project (L.E.A.P. study) which prospectively enrolled 545 patients in 8 level I trauma centres in the United States. Analysis of these data unexpectedly revealed a functional outcome and resulting quality of life following either intense reconstruction or amputation which are in fact comparable (6). Additionally, the L.E.A.P. study data also have put into question the validity of scores known and expected to be predictive in the decision making for limb salvage or amputation. As low scores were found to be predictive for limb salvage potential high score results have failed to support the validity of predicting amputation. Interestingly, Doukas et al. presented the M.E.T.A.L.S. (Military Extremity Trauma Association/limb salvage) study in which they compared limb salvage versus amputation among soldiers injured during combat. They concluded, that amputees had a better functional outcome than those with salvaged limbs (14). However, that study included mostly blast injuries and shotgun/gunshot wounds making direct comparison of the data impossible. About 20% of all patients treated in emergency rooms present with an injury severity score (ISS) higher than 15 (58). Court-Brown et al. were able to show a positive correlation between the incidence of open fractures and corresponding individual Injury Severity Score (ISS) (12). Consequently, due to the complex injury pattern of the extremity and the overall situation of multiple injured patients the treatment and decision making has to be made in a priority-adapted algorithm (Figs 1 and 2). In this treatment algorithm interdisciplinary cooperation with vascular and plastic surgeons is of tremendous importance. Although the number of severely injured patients remained stable in the last decade, changes in the treatment algorithms result from increased survival rates of multiple injured patients and improved modern reconstructive options leading to continuously increasing rates of salvaged limbs (47). New, soft tissue preserving, surgical approaches (MIPO techniques, percutaneous osteosynthesis), innovative microsurgical techniques for soft tissue coverage including local and free vascularised tissue transfers (vascularised bone transfer, local and free muscle flaps) in combination with modern fixation techniques, e. g. anatomically preformed and angular stable implants have improved the results and are an integral element of a contemporary priority based treatment algorithm.

This paper aimed to systematically review the current body of literature for lower extremity injuries in order to unravel the different surgical options and provide guide-

lines for decision making with corresponding treatment algorithms for limb salvage. Furthermore, the experiences in the management of mangled extremities in our centre are presented and underscored with illustrated cases.

EPIDEMIOLOGY

Court-Brown *et al.* published in 1998 an epidemiologic study in which the authors could show an incidence of open long bone fractures of 11.5/100,000 per year with 291 of 515 involving the lower limb. Male patients were affected more often and the main causes for injury were traffic accidents (about 60%) followed by simple falls (in 20%). Falls from great heights as well as sport accidents were seen in 10% of the cases, while another 5% resulted from direct impact traumata, criminal assaults or crush injuries (12). In 2012, again Court-Brown and associates published another study, which included 2386 open long bone fractures over a 15 years period. Within this population an overall incidence of open long bone fractures of 30.7/100,000 per year was seen, with 42.6% of all grade III open fractures affecting the lower limb (11).

PATHOPHYSIOLOGY OF SEVERE SOFT TISSUE DAMAGE

The most important pathway underlying the traumatic soft tissue damage is the local disruption of capillary perfusion resulting in ischaemia, local hypoxia with consecutive nutritive and metabolic disturbances. Beside the acute traumatic destruction of vascular structures and soft tissue parenchyma by the traumatic impact itself, the trauma energy leads to on-going detrimental microcirculatory changes (57). In addition, the direct soft tissue destruction leads to an activation and recruitment of macrophages and neutrophils as well as to a massive release and distribution of proinflammatory mediators like histamine, cytokines and metabolites of arachidonic acid (60). This process again converges via breakdown of the capillary endothelial integrity to increased capillary permeability resulting in massive interstitial oedema which – in turn – causes elevated tissue pressure and compromised nutritive perfusion. This vicious circle is further associated by the liberation of catecholamines and glucocorticoids from activated leukocytes and endothelial cells which additionally promote the local ischaemia and hypoxic metabolic status also in tissue areas around the initial traumatic impact zone/tissue destruction. This phenomenon, termed as secondary tissue damage, leads to a progressive necrosis of initially viable tissue surrounding the impact zone. Depending on the extent and severity of the trauma as well as individual immunological defence mechanisms, local consequences of posttraumatic inflammation have the potential to lead to systemic escalation of the inflammatory processes (57). Proinflammatory stimuli can overwhelm the whole organism leading to damage or even failure of further organs (remote organ

Table 1. Classification of soft tissue damages according to Tscherné (31) and Gustilo/Anderson (27, 28)

Tscherné	Gustilo/Anderson	Description
O1	I	Superficial, clean wound conditions of less than 1 cm
O2	II, IIIA	Deep contaminated wound (> 1 cm), soft tissue contusion, adequate bone coverage, pre-compartment
O3	IIIB	Broad soft tissue defect (contusion, décollement), loss of periosteal coverage
O4	IIIC	Broad soft tissue defect (contusion, décollement), arterial vessel injury which has to be reconstructed

failure, multi organ dysfunction syndrome, MODS) and a systemic inflammatory process of multiple organ systems, i. e. SIRS (systemic inflammatory response syndrome) (36, 59). MODS is probably a confluence of an uncontrolled systemic inflammatory response involving multiple pathways and an imbalance of pro- and anti-inflammatory mediators (37). There is clinical and experimental evidence that the nitric oxide system (NO-system) plays a substantial role in evolving posttraumatic microcirculatory disorders. (1, 17, 53). This notion is supported by findings that show a reduced NO-synthesis during ischaemia or re-perfusion which leads to an increase of the leukocyte adherence as well as the production of superoxide radicals, one of the first signs of endothelial dysfunction. Other experimental studies could demonstrate, that a NO induced host-defence-mechanism may influence the pathology of traumatic muscle ischaemia (56). Further studies are needed to understand these pathways in order to utilize potential findings for effective treatment aimed at disruption of the underlying microcirculatory and inflammatory vicious circle, thus preventing the escalation of disease.

CLASSIFICATION

The first step in effective salvaging a mangled lower limb is to exactly classify the defect/soft tissue trauma. To date, many classifications for soft tissue damage have been published. Among these nomenclatures only two are mainly accepted and used for the assessment of closed and open soft tissue damage. For classification of the open soft tissue damage, the classification of Gustilo and Anderson (26) (Table 1) developed in the year 1976 and modified 1987 (27) is most commonly used and accepted worldwide, although some authors criticize it because of its relatively high interobserver variability (7, 30).

Even though the classification developed by Tscherné et al. handles with closed and open soft tissue damage (61) (Table 1), it is prevalently used for classifying closed soft tissue damages. Both classifications are criticized for the same reasons. In fact, interobserver variability is high as individual assessment depends on the clinical experience of the evaluating surgeon. Another concern is the fact that in closed soft tissue damage the real extent of soft tissue trauma is not clearly evaluable as it is hidden under a damaged but intact skin and retracts therefore from exact assessment. In addition the damaged muscle and skin can become necrotic over

time during the later course, resulting in devastating conditions (secondary tissue damage). A clear correlation could be shown between the severity of the soft tissue damage and the infection rate (type I: 0–2%, type II: 2–5%, type IIIA: 5–10%, type IIIB: 10–50%, type IIIC: 25–50%) (49). To date, clinical reliable prognostic tests or factors allowing a preoperative differentiation between reversible (vital) and irreversible (nonvital) soft tissue damage are missing, although some modern imaging systems allow qualitative assessment of tissue perfusion and damage. The initial soft tissue damage is often underestimated in the first clinical assessment. The intraoperative assessment during the first debridement often shows a far higher grade of soft tissue damage than preoperatively assumed. Therefore, the real grade of initial soft tissue damage can only be classified intraoperatively (33). Due to evolving secondary damage, it is of essential importance to realize that the soft tissue damage is not a stable condition, indicating that the evaluation of the soft tissue damage has to be an ongoing process (serial, sequential assessments) with a post primary “upgrading” of the soft tissue damage classification during the first 24–48 hours after admission. Pursuing this approach of repetitive estimation of the soft tissue damage allows for timely surgical revisions in order to prevent crucial complications (i. e. deep infection).

The definition of a subtotal amputation per se implies always the destruction of the most important anatomical structures including the principal neurovascular structures (ischaemia, grade IIIC /O4 open fracture), leaving only a residual soft tissue bridge of less than one-quarter of the circumference and (3). For comparison of the late functional results, Biemer et al. subclassified the subtotal amputation according to the proportion and rate of structures that remained intact (2).

INITIAL ASSESSMENT AND DIAGNOSTICS

General considerations

Complex fractures with severe open soft tissue trauma often occur in multiple injured patients. There is a positive correlation between the incidence of open fractures and the overall ISS (injury severity score) (12). Consequently, a priority adapted, standardized approach as exemplified by the most widely used ATLS® concept (advanced trauma life support®) is needed that guides a staged treatment cascade. Apart from the overall haemodynamic situation of the patient (haemorrhagic shock, additional organ injuries) the

Table 2. Components of different injury scores for evaluating the lower limb (modified after [7]); MESS: Mangled Extremity Score; LSI: Limb Salvage Index; PSI: Predictive Salvage Index; NISSA: Nerve injury, Ischemia, Soft tissue injury, Skeletal injury, Shock, Age of patient; HFS-97: Hannover Fracture Scale (Version 1997).

Score	MESS	LSI	PSI	NISSA	HFS-97
Age	X			X	
Shock	X			X	X
Ischemia time	X	X	X	X	X
Fracture		X	X		X
Muscle injury		X	X		
Skin injury		X			X
Nerve injury		X		X	X
Deep vein injury		X			
Skeletal and soft tissue damage	X			X	
Contamination				X	X
Time until treatment			X		

therapeutic strategy decisively depends on the ischaemia time of the extremity. Securing and stabilizing the haemodynamic and pulmonary situation is the first priority beside all intentions of potential limb salvage. In particular, life threatening multi-organ injuries with the presence of initial haemorrhagic shock extremely complicates a realistic decision making for the potential of limb salvage and requires tremendous clinical experience. Replantation, notably of the lower limb, is contraindicated in such a critical overall situation or in patients with a high ISS (39) as it exposes the patient to additional risks caused by longer operation times, further blood loss, local/systemic inflammations, which in turn increase mortality. Injury- (ischaemia time, fracture type, degree of soft tissue damage) and individual patient-specific (age, comorbidities, smoking, compliance) factors have to be considered in the future treatment concept. The high number of different scores that have been developed and designed to assist in the difficult decision whether primary amputation or reconstruction is the prognostically most favourable strategy reflects the insufficiency in clinical applicability and individual problems of their use (Table 2). Since these scores include and consider partly different parameters like age of patients, ischaemia time, degree and type of vascular, nerve/muscle injury and fracture type to a variable extent their sensitivity and specificity is erratic and inconclusive (5). Nevertheless, combined application of these scores may somehow help to make the individual patient's situation more clear and objectify the individual injury pattern. However, in particular for monotrauma patients, these scores do not have the potential to serve as an absolute tool or substitute for individual decision making. The basic decision to perform amputation or reconstruction is rather made on the synopsis of clinical aspect, associated injury of neurovascular structures, the degree of contamination, the duration of ischaemia prior to admittance and severity of the soft tissue damage and fracture type of the mangled extremity (54). In particular the type of soft tissue trauma and its contamination (penetrating or blunt trauma, tangential decollement-forces, degloving, blast

injury etc.) has turned out to be the most predictive and decisive factor adversely determining the success for limb salvage.

Antibiotic therapy and tetanus vaccination

The selection of calculated antibiotics should cover gram-negative as well as gram-positive germs and should be administered as soon as possible but not later than 3 hours after trauma. It is recommended to take a probe of the contaminated site before administering the antibiotics in order to adapt the regime to found resistances. Delayed onset of the antibiotic therapy have been shown to increase the risk of infection (49). First generation cephalosporins (gram-positive spectrum) in combination with an aminoglycoside (gram-negative spectrum) are recommended. Aminoglycoside can be replaced by chinolones, aztreonam or third generation cephalosporins alternatively. If anaerobic germs are expected to be involved, as typically seen in wounds of farmers, an additional ampicillin or penicillin is advised (48, 65).

As considered in all wounds the tetanus vaccination status should be checked and performed for all patients who had the last vaccination more than five years ago or patients with unknown status of vaccination (http://www.who.int/immunization/policy/immunization_tables/en/index.html).

Inspection and immobilization

During the initial assessment in the emergency room the most experienced surgeon available should inspect the wounds and assess the degree/classify the soft tissue damage. Repeated or serial reopening of the wound dressings for demonstration purposes prior to the arrival in the operation theatre should be avoided. Nowadays, initial photo documentation is considered to be standard. Microbiologic probes are taken before disinfection is done. Following direct fracture reduction by traction a sterile dressing should be applied immediately to stop ongoing contamination and to protect the exposed vulnerable structures. Thereafter, sufficient immobilization is required which is best done by inflatable splints. Ho-

wever, high air pressure in these splints has to be prevented in order to avoid further soft tissue damage. As mild external soft tissue compression by inflated splints can increase intracompartmental pressure they are an absolute contraindication in presence of a manifest or impending compartment syndrome, which then requires a different form of immobilisation, e. g. braces or traction tools.

First line diagnostics

Plain biplanar radiographs of the injured region including the proximal and distal joints are essential for all following considerations. While inspecting the wound the peripheral vascular status has to be documented (pulse distal to the injury, skin colour, and capillary refill). If no pulse can be detected clinically, effective fracture reduction by simple traction has to be re-checked in order to exclude vascular disruption/injury as dislocation-induced vessel kinking with temporary ischaemia can mimic vascular injuries. A duplex ultrasound should be performed before and after fracture reduction when peripheral pulse and vascular status is questionable. Although sensitivity and validity for detection of ischaemia/vascular injuries of duplex ultrasound are reaching nearly same level when compared to invasive conventional angiography, this technique is still dependent on the experience of the observer (34, 46). For detailed diagnostics the development of newer techniques as the multi slice CT angiography including 3D-reconstructions has led to a decrease in the use of conventional angiography (18, 23). Thus, an invasive, digital subtraction-angiography is indicated less frequent than in former times and more restrictively performed (8, 21, 50).

The main indications to perform a CT-angiography are:

- Closed fracture with inability to localize the vascular injury clinically
- In case of an suspected intima flap following traction damage, the CT-angiography has to rule out whether an endovascular therapy can be performed
- If the pulselessness is proximal the level of the wound
- Segmental fracture, with the chance of injury to the vascular structures at different levels
- Nowadays conventional angiography is rather used in situations when an interventional endovascular procedure has to be performed (e. g. stent implantation, embolization)

Diagnostic of compartments syndrome

Open tibia fractures are associated with a rate of consecutive compartment syndrome of up to 10% (4). Typical initial symptoms include severe pain that is resistant to all known analgetics and aggravates during dorsal extension in the ankle joint. In addition massive swelling with bright skin and indurated muscle loges are characteristic signs. In the later course skin necrosis with blistering and neural dysfunction, starting with dysesthesia between the first and second toe as a consequence of a lesion to the profound peroneal nerve

branch can be found. From the pathophysiological point of view a compartment syndrome is caused by an increase in the tissue pressure level exceeding the capillary perfusion pressure which results in a failure and breakdown of nutritive skeletal muscle microcirculation. Therefore, the rate of non-recognized compartments syndrome is higher in polytraumatized patients who are sedated, intubated and unable to report key symptoms like pain and numbness and – more important – additionally suffer from impaired macrohaemodynamics caused by haemorrhagic shock. Consequently special attention must be paid to those patients and the indication for emergency fasciotomy should be set rather generous allowing the intramuscular pressure to decline. It is widely accepted that the most important parameter, i. e. capillary perfusion (difference between the diastolic and the intra-compartmental pressure) should not fall below a critical threshold of 20 – 30 mmHg (15, 40, 62). In fact, in case of clinical doubt a compartment pressure measurement can be performed in order to confirm the diagnosis (10, 32).

Severe and fulminant compartment syndromes are also observed following prolonged ischaemic period and revascularization surgeries as a result of massive reperfusion oedema and subsequent increase in tissue swelling and pressure. In these patients a prophylactic fasciotomy is mandatory in order to ensure a sufficient capillary perfusion, adequate postcapillary outflow and arterial run off.

If a lower leg compartment syndrome is suspected, a four-compartment fasciotomy is recommended. This should be performed via a single lateral incision or by a double lateral/ medial approach technique (32, 43). The single incision technique allows adequate exposure of all four compartments. Even in high grade open fractures with traumatic opening of the compartments a complete fasciotomy should be performed in order to ensure that the compartmental pressure can be reduced.

PREOPERATIVE CONSIDERATIONS AND DECISION MAKING

The strategy and sequence of treatment options of complex extremity injuries is determined by the type of fracture and the concomitant soft tissue damage, the duration of warm ischaemic period and the overall situation of the patient (additional injuries of other organ systems, the presence of shock) (55). Replantation, in particular of the lower limb, is contraindicated in critical overall situations in combination with high polytrauma scores (“life before limb”) (39). In monotrauma patients the decision for limb salvage or primary amputation primarily depends on the grade of soft tissue injury as well as the degree of nerve injury most adversely impacting the long term outcome. In view of the duration of ischaemia it could be shown that an warm ischaemia time over 6 hours tremendously reduces the chance of success (42). However, cold ischaemia durations (4–8°, ice water) longer than 6 hours, up to 8 hours are incidentally reported to be acceptable for replantation.

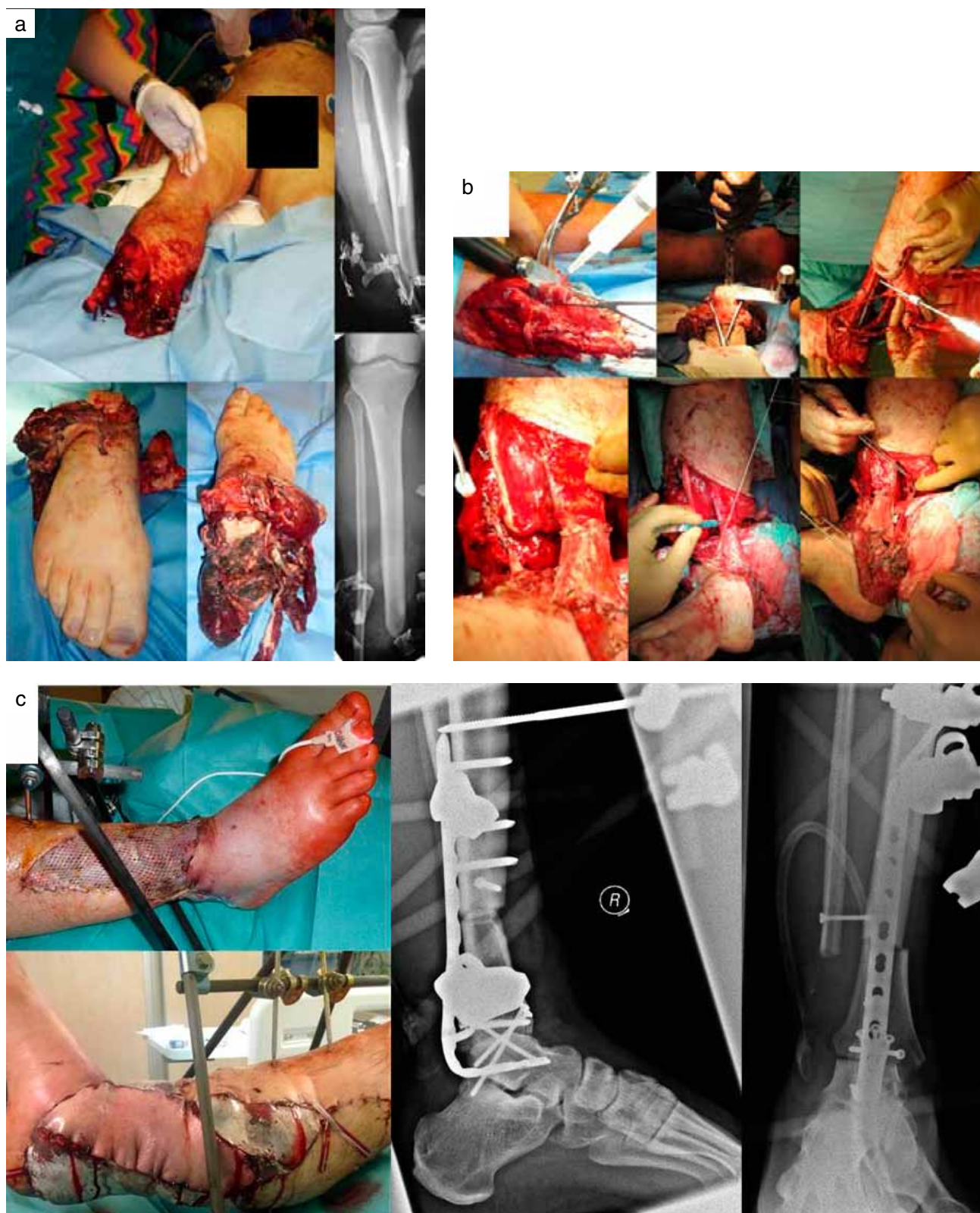


Fig. 3a. 46-year-old male patient who was hit by a running train. At admission the patient showed this IIIC open distal tibia fracture with macro-amputation of the complete distal lower limb as a monotrauma injury. As the amputate did not show a severe soft tissue damage and the warm ischaemia time was below 4 h the indication for replantation was made.

Fig. 3b. According to our algorithm (Fig. 2) the reconstruction of the bone was made prior to vascular reconstruction. In this case a primary arthrodesis of the upper and lower ankle joint was performed using an angular stable blade plate osteosynthesis (4.5 mm LCP, Synthes). Due to the shortening of the leg an end-to-end suture of the artery was possible.

Fig. 3c. After serial debridements an early soft tissue coverage using a free vascularised soft tissue flap in combination with MESH graft of the residual defect could be achieved 10 days after replantation. The postoperative X-ray shows a good alignment of the lower limb in both plains.

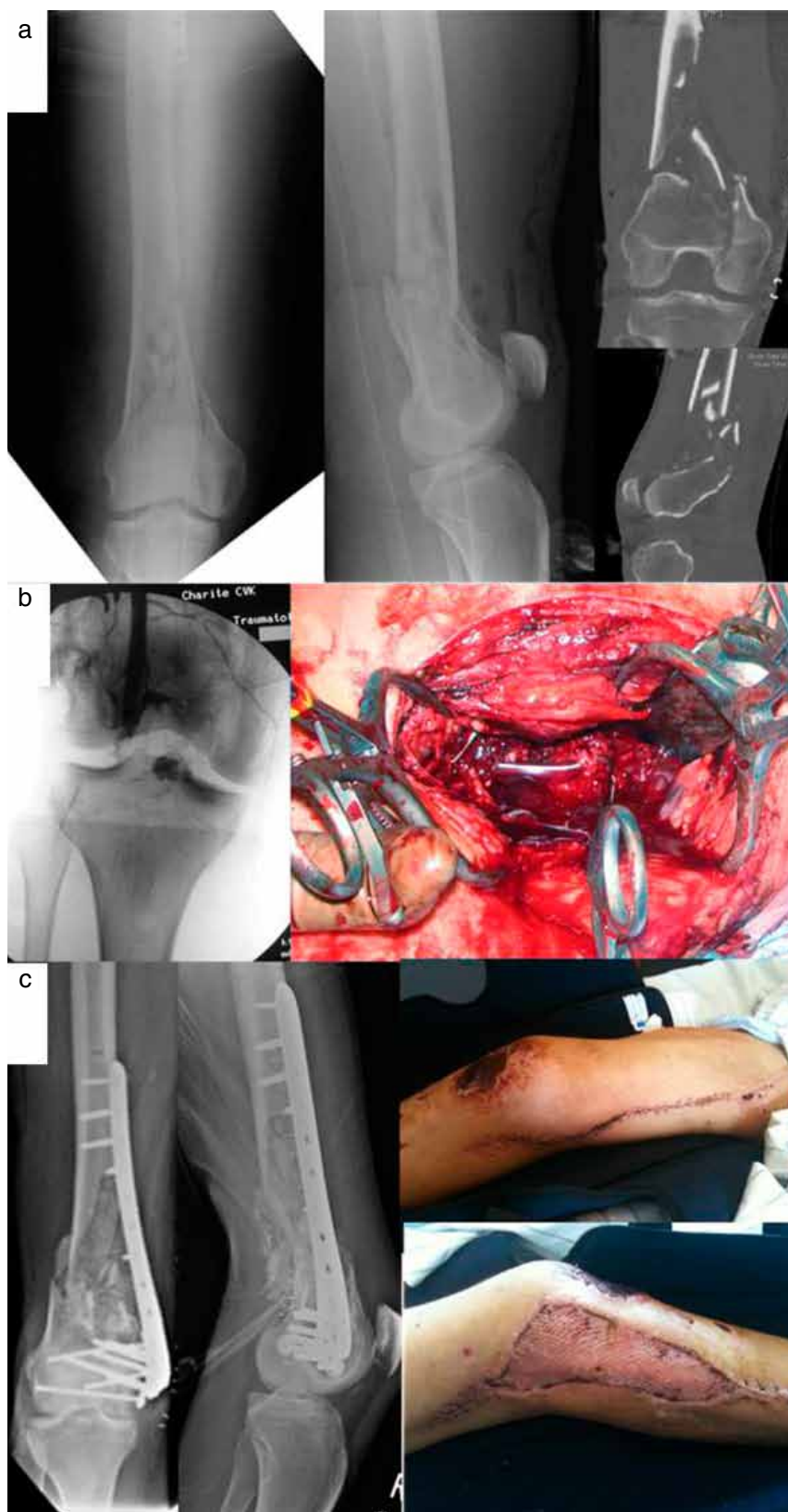


Fig. 4. IIIC open distal femur fracture (43-C2 acc. AO) of a 44-year-old male patient after a high velocity traffic accident (upper row). The intraoperative angiography shows a rupture of the popliteal artery distal to the fracture. In order to shorten the warm ischaemia time a temporary heparin coated shunt was inserted while the venous autograft (great saphenous vein) was prepared for implantation (middle row). After serial debridements the definitive osteosynthetic reconstruction (L.I.S.S., Synthes) as well as the early soft tissue coverage (MESH graft) was achieved.

TREATMENT ALGORITHM

Once the decision of replantation is made (Fig. 1), a multidisciplinary approach is followed with a sequence of reconstructive measures for vascular/nerve repair, fracture reduction and fixation (Figs 2 and 3a – c).

Debridement

The initial debridement is the decisive step during the initial phase to prevent infections leading to an undisturbed bone healing. Therefore, the soft tissue has to be decontaminated sufficiently not only of foreign bodies but also of necrotic soft tissue which increases susceptibility to infection and contributes to inflammation and regional ischaemia. Since the clinical experience has shown, that during the course initially vital soft tissue turns out to become necrotic over time the second and third look debridements are necessary within the next 48 hours and have to be performed in the same radical way in order to prevent infections or thromboembolic complications of the reconstructed vascular structures. This so called “secondary damage” requires exact re-evaluation and reclassification of the soft tissue damage during the following surgeries (55). Objective criteria for a “radical” performed debridement do not exist and often depend on the training and experience of the surgeon. Preserving questionable viable soft tissue for functional aspects does not play a primary role except the preservation of neurologic structures.

In this context it should be mentioned, that a prophylactic dermatofasciotomy should be performed in patients following vessel reconstruction after an ischaemia time more than 2–3 hours. In cases of unclear ischaemia time or severe soft tissue damage in closed and open fractures we perform a dermatofasciotomy in order to prevent an unrecognized transition from impending to manifest compartment syndrome. After the debridement is done the soft tissue is covered using artificial skin substitutes (Epigard®, Orthomed, Vienna, Austria). In our

experience vacuum assisted closure (V. A. C.[®]) is not recommended for coverage after initial debridement as the acutely damaged skin does initially not benefit from tangential shear caused by adhesive foil fixation needed to seal the vacuum.

Vessel reconstruction

The successful revascularisation is the most important determinant in terms of potential complications after an IIIC open extremity injury. Therefore, it is in first place of the treatment algorithm. All other subsequent therapeutic steps, procedures and decisions directly depend on the successful reperfusion. In addition the control of blood loss can only be managed by vessel repair. Whenever possible an end-to-end-anastomosis should be tried. Primary shortening in case of segmental bone loss or after debridement of avital or devascularized bone fragments often allows beside the decrease of compartment pressure (due to increased compartment volume) a direct anastomosis without graft interposition. If necessary, autologous venous grafts (e. g. the great saphenous vein or the femoral vein) of the injured or even better the contralateral side (higher rate of thrombosis of ipsilateral grafts due to the trauma and decreased venous drainage of the injured leg) should be preferred. Allogenic materials should be avoided because of the high risk for infection. The sequence of reconstruction depends on different factors. If the warm ischaemia time (< 4 h) allows, the fracture reduction and stabilization is done first (in most cases by external fixation) determining the definitive length of the extremity. Furthermore, the reduction/stabilization protects the anastomosis from tractional and shear forces preventing re-ruptures, intima lesions, dissections or kinking. However, if the warm ischaemia time exceeds the tolerance limit (> 4 h) and needed time for debridement and stabilization is expected to be prolonged, the vessel reconstruction should be done in first place. In some cases the use of a temporary intraluminal shunt can help to shorten the ischaemic time until the definitive vessel reconstruction is performed (Fig. 4). Meanwhile other acute procedures can be done or the patient can be transferred to a centre of higher competence (39). While using this method it has to be kept in mind that after arterial reperfusion via shunt relevant blood loss through reperfused but injured veins can occur. In cases of cold ischaemia the ischaemic tolerance is higher concerning the time interval because of cooling-induced down regulation of tissue metabolism (58).

Reconstruction of neurologic structures

The long-term functional outcome of the salvaged extremity is mainly determined by the reconstruction of neuronal structures. Factors influencing the outcome are the type of injury (segmental tissue loss, sharp ruptures), the level of disruption, the comorbidities as well as the age of the patient. Sharp ruptures have a better prognosis than traction- or defect injuries (25). In 85% of all cases the neuronal structures are completely disrupted (52). In cases of severe neurologic injuries an

interdisciplinary cooperation (micro-, neurosurgery) is of extraordinary importance. Whenever possible a primary microsurgical nerve-suture should be performed. Peripheral nerves are remarkable sensitive to ischaemic conditions. Because neuronal structures cannot withstand tractional forces (10% elongation leads to 50% decrease in neuronal blood flow), the anastomose has to be strainless (38). Many suture techniques have been described in which the primary epineural end-to-end-suture is to be preferred. To date, it could be shown that this suture technique has comparable clinical results to the interfascicular suture but a decreased scar tissue rate (64). The interfascicular suture is recommended for large calibre nerves where motoric and sensory bundles can be discriminated. For rotational control the accompanying vessels can be helpful for intraoperative orientation. In cases of segmental tissue loss a secondary or tertiary reconstruction using grafts is recommended. In those situations autogenic grafts are used either from the not reconstructable section of the injured extremity or from other donor sites like the medial or lateral cutaneous antebrachial nerve, the lateral femoral cutaneous nerve, intercostal nerves or the sural nerve. The sural nerve for instance can be used to bridge a defect length of 40 cm in maximum without significant donor site morbidity. In order to secure the blood supply of the graft it should be 10 – 20% longer than the defect itself. The secondary reconstruction should be performed within 3 – 6 month after trauma (52).

The remaining 15% of the injuries accompanied by neuronal deficits are partial lesions arising from traction forces. In those cases the spontaneous recovery should be awaited before secondary intervention is enforced (31).

Fracture stabilization

The fracture reduction and stable fixation using different techniques plays a central role in the reconstructive algorithm for mangled extremities. The stabilization leads to a decrease in pain, reduces the infection rate and is a basic requirement for soft tissue preservation and wound healing. Furthermore it secures the arterial reconstruction and influences the venous flow positively. In multiple injured patients the skeletal stabilization leads to a reduction of hyperinflammation as well as other responses of the immune system thereby reducing the risk for MOF (**multi organ failure**) (41, 45). The management of fracture stabilization and its timing depends on

- the degree of the open or closed soft tissue damage (compartment syndrome, ischaemia time, degree of contamination)
- the fracture localisation (dia-/metaphyseal)
- the fracture type (intra-/extra-articular, simple/multifragmentary, bone defect, segmental bone loss)
- co-morbidities

For fracture stabilization the following techniques are widely accepted and established:

- external fixation (for primary or definitive fracture care)
- intramedullary techniques (reamed/unreamed ante-/retrograde nailing, K-wires)
- plate-/screw osteosynthesis (open/MIPO, percutaneous, conventional/angular stable systems)
- combinations of the above named

Due to the easy and fast technique to reduce and stabilize any fracture, the external fixator is the most used technique for primary fracture management during the damage-control-strategy. Furthermore, in selected cases the external stabilization can serve as definitive fracture care (29, 51). For definitive stabilization the aims defined by the AO namely reconstruction of the articular surface without steps or gaps (using absolute stability) as well as length, rotation and axis for restoration of shaft fractures, have to be kept in mind. Whether intra- or extra-medullary (nail versus plate/screws) methods are used depends on the type and localisation of the underlying fracture.

Soft tissue coverage

The goals of soft tissue reconstruction are the restoration of a sufficiently closed soft tissue envelope, the early coverage of vulnerable neurovascular structures as well as the coverage of the fractured bone with a viable, non-infected soft tissue envelope. A detailed analysis of the local wound conditions has to precede the performance of the final reconstruction method. Primary wound closure via sutures is only recommended after the initial radical debridement in patients with grade I or more rarely grade II open fractures when closure can be achieved with only mild to moderate traction to the well-perfused soft tissue. Recent studies could demonstrate that in selected patients it does not lead to higher infection rates or delayed wound healing compared to secondary closure (65). In fractures that show significant wound contamination serial debridements, temporary closure (Epigard®, Orthomed, Vienna, Austria or Vacuum Assisted Closure, V. A. C.®, KCI, San Antonio, TX, USA) followed by secondary closure is considered the standard of care. Usually, the definitive wound closure can be achieved after 5 – 7 days by direct suture or MESH-graft. The major criterion for a successful MESH graft is the underlying soft tissue condition which can positively be influenced by serial debridements and the use of VAC-therapy. If neurovascular structures, tendons or deperiostated bone are exposed the MESH technique is not useful and feasible. These situations represent an indication for a local or free soft tissue transfer. The quality of underlying/surrounding soft tissue, the degree of contamination and the circumstances of arterial and venous anastomosis (direct suture, venous grafts or loops, length and course of vascular pedicle) are known factors influencing flap failure rate.

Basically the decision which type of flap (local or free flap transfer) is appropriate depends on local conditions (size, depth and locations of the defect) as well as pre-existing patient characteristics (smoker, co-morbidities,

patients demand). There are several options for defect reconstruction:

- local, not pedunculated soft tissue transfer (local muscle transfer covered with MESH graft)
- local pedunculated soft tissue transfer (e. g. gastrocnemius or soleus flap)
- fasciocutaneous flap (e. g. radialis or suralis flap)
- free flap (e. g. latissimus flap)

Accumulating clinical evidence suggests that an early soft tissue coverage within the first 2–5 days after the first surgery leads to the best results in terms of less flap failures (flap thrombosis), minimized infection rates, reduced hospitalization times and better fracture healing (24). Performance of an “emergency free flap” for higher degree open fractures is a very rare indication and part of the “one stage reconstruction” concept (63). The authors suggest that this concept minimizes a superinfection and further damage of the soft tissue. However, this concept requires a radical and meticulous initial debridement as any evolving secondary soft tissue damage is difficult to predict and defies any assessment and treatment. A rare indication for an emergency flap procedure may be given in cases of decapsulated joints with missing options for soft tissue coverage of the joint surface.

CONCLUSION

Salvaging a lower limb continues to represent to be a major challenge for the orthopaedic surgeon. Today the surgical techniques (osteosyntheses, microsurgical methods, plastic flap transfers) are advanced, well developed and lead – if performed accurately and for the correct indications – to a good functional outcome, acceptable posttraumatic quality of life as well as social and economic re-integration of the patient. Exact classification and application of a priority adapted concept are the key factors that guide timing and mode of fracture treatment and finally determine success of all efforts aimed at limb salvage. The results of the prospective multicenter L.E.A.P.-study have impressively shown that limb salvage for IIIC open fractures may result in functional results and secondary psychological disturbances not worse than amputation. Moreover, disturbances in body integrity, exo-prosthesis related problems and rising socioeconomic costs could be minimized. The treatment concept follows a detailed algorithm which has to be adapted to the type of injury (mono- versus polytrauma), severity of soft tissue damage and individual patient characteristics. Advanced reconstructive methods with minimally invasive approaches, modern angular stable implants and microsurgical methods, incl. free/vascularised bone/tissue transfer have shifted the treatment towards increased tendency for limb salvage and reduced rates of primary amputation. However, a serial assessment of the injury, a prognostic anticipation of the healing course and surgical outcome along with a realistic appreciation of the overall patient's status is mandatory in order to avoid that a burning ambition of the reconstructive surgeon may expose the patient at vital systemic risk (“life

before limb"). Therefore, a high expert knowledge of the surgeon adhering to the staged algorithm and an interdisciplinary team approach (orthopaedic, neuro-, vascular surgery, intensive care medicine) most likely holds the key to improve the final outcome and regain of extremity function.

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