Published in final edited form as:

Foot Ankle Clin. 2010 March ; 15(1): 113–138. doi:10.1016/j.fcl.2009.10.006.

Soft Tissue Management of War Wounds to the Foot and Ankle

Martin F. Baechler, MD^{a,b,*}, Adam T. Groth, MD^c, Leon J. Nesti, MD, PhD^{d,e}, and Barry D. Martin, MD^{b,f}

^a Department of Orthopaedics and Rehabilitation, Walter Reed Army Medical Center, 6900 Georgia Avenue, NW, Washington, DC 20307, USA

^b Department of Surgery, Uniformed Services University of the Health Sciences, 4301 Jones Bridge Road, Bethesda, MD 20814, USA

^c Department of Surgery, Orthopaedic Surgery Service, Tripler Army Medical Center, 1 Jarrett White Road, Honolulu, HI 96859, USA

^d Department of Surgery, Orthopaedic Surgery Service, McDonald Army Community Hospital, 576 Jefferson Avenue, Fort Eustis, VA 23604, USA

^e Clinical and Experimental Orthopaedics, National Institute of Arthritis, Musculoskeletal, and Skin Diseases, National Institutes of Health, Building 50, Room 1140, 50 South Drive, MSC 8022, Bethesda, MD 20892, USA

^f Department of Surgery, Integrated Plastic Surgery Service, Walter Reed Army Medical Center, 6900 Georgia Avenue NW, Washington, DC 20307, USA

Abstract

The recent conflicts in Iraq and Afghanistan have resulted in severe foot and ankle wounds to many United States service members. Amputation of the severely damaged extremity often is the only option, while amputation of the potentially salvageable extremity may be chosen by the patient and the surgeon as the preferred reconstructive treatment.¹ When salvage is pursued, enormous challenges are encountered in managing the complex wounds of war. The cumulative experiences of military surgeons have been invaluable in advancing reconstructive surgery of the war-wounded foot and ankle.^{2,3} This work details the experiences of United States military reconstructive surgeons in the soft tissue management of the war wounds of the foot and ankle resulting from the conflicts in Iraq and Afghanistan.

Keywords

War; Foot; Ankle; Flap; Reconstruction; Microsurgery

INDICATIONS FOR FLAP COVERAGE

Certainly not all foot and ankle war wounds require flap coverage. Wounds of relatively low complexity may be satisfactorily treated with delayed primary closure, healing by secondary intention, early skin grafting over a suitable bed, or delayed skin grafting after a period of dressing changes or sub-atmospheric wound dressing.⁴ However, wounds that are more complex, with exposed fracture, joint, nerve, tendon lacking paratenon, and bone lacking

*Corresponding author. Department of Orthopaedics and Rehabilitation, Walter Reed Army Medical Center, 6900 Georgia Avenue, NW, Washington, DC 20307. martin.baechler@us.army.mil (M.F. Baechler).

periosteum, frequently require flap coverage simply to achieve wound healing and further to maximize eventual function of the aforementioned critical structures (Figs. 1 and 2).

It is common in war wounds for critical structures to be segmentally deficient. While such wounds may be vascular and support a skin graft, flap coverage is often necessary to prepare for future reconstruction of deficient structures. Defects of nerve, tendon, ligament, joint, and even bone typically are not reconstructed at the time of flap coverage of these wounds. Waiting until the flap has matured and wound inflammation has resolved promotes improved outcomes of reconstructive procedures by reducing scar formation and the risk of infection. For example, nerve grafting in the acute period is not recommended because the degree of injury of the truncated nerve ends is commonly underestimated. Truncated nerve ends within the zone of injury may appear to have retained fascicular architecture in the acute period, but may devolve into dense scar, which blocks axonal sprouting to a nerve graft. Indeed, at the time of delayed nerve grafting of war wounds, the surgeon routinely must trim the truncated nerve ends by a centimeter or more until fresh, normal appearing fascicles are found. Likewise, tendons should be reconstructed, or transferred, in a delayed fashion, to avoid excessive scarring caused by the inflammation of the acute injury, and also because the early rehabilitation requirements of tendon reconstruction may compete with those of initial wound healing. However, the surgeon may consider placing silicone rods underneath flaps to create a favorable tunnel for tendon grafting. Bone graft is often delayed due to the risk of infection and graft resorption. Methylmethacrylate spacers are very useful under flaps to preserve space for eventual bone grafting. In wounds with smaller bone deficits, osteoconductive materials such as calcium sulfate may be considered. Furthermore, antibiotic impregnated methylmethacrylate and calcium sulfate have been shown in laboratory animals to reduce infection rates.⁵⁻⁷

PLANTAR SURFACE RECONSTRUCTION

Flap coverage to the plantar surface may be necessary to treat exposed critical structures. There is debate on the emphasis that should be placed on the sensory characteristics of the reconstructed plantar surface. If a suitable recipient nerve is available in proximity to the wound, both coverage and flap sensation are possible with nerve coaptation. Sensory reinnervation can yield light touch sensibility in most cases, and temperature sensibility occasionally. In general, 2-point discrimination does not occur. Many neurosensory flaps have been described for microvascular transplantation in an effort to provide sensation to plantar reconstructions. Two useful donor sites that have been described for use in the foot and ankle are the deltoid⁸ and lateral arm flaps.⁹ The donor site scar in each case may be undesirable, but both have reliable neurovascular anatomy and are relatively thin. In one study, the use of reinnervated free radial forearm flap reconstruction to the heel, with coaptation of the lateral antebrachial cutaneous nerve to the sural nerve, was compared with the outcomes of noninnervated flaps. Improved sensibility was achieved with sensory reinnervation of the free flap but improved clinical outcomes were not definitively shown.¹⁰

Indeed, most investigators agree that recovery of sensibility is not critical to achieve stable, long-term coverage, as no correlation has been demonstrated between ulcer occurrence and sensibility.¹¹ Many investigators have reported successful, durable coverage of the plantar surface after free muscle transfer and skin grafting, and have concluded that the presence of light touch sensation did not correlate with successful reconstruction.¹²⁻¹⁴ Deep pressure sensibility has been demonstrated early in the postoperative period for both fasciocutaneous transfers without sensory nerve coaptation as well as for free muscle flaps covered with skin graft.¹⁵ Thus, sensory nerve coaptation may not be required.¹² Reports assessing sensory nerve repair to the motor nerves of free muscle transplants and the implantation of sensory nerves directly between the muscle surface and the skin graft have been published.¹⁶

However, large prospective studies have not been reported. These reinnervation techniques have not been routinely employed in the authors' patient population.

There is also debate over what is the best tissue to place on the plantar surface. Muscle flaps have the tendency to adhere to underlying surfaces, which has the favorable effect of resisting the shear forces on the plantar surface. However, the skin graft that is necessary over a muscle flap may contract and distort native skin edges, possibly leading to dermadesis across joints. Fasciocutaneous flaps will guard against wound contracture as well as promote joint mobility due to the aggregate elasticity of the full complement of dermis, subcutaneous tissue, and fascia. However, this same quality of fasciocutaneous flaps makes them more vulnerable than muscle to the shear forces on the plantar surface. Of note, circular wounds, even when covered with a fasciocutaneous flap, may be prone to centripetal contracture due to the action of myofibroblasts at the wound edge. Therefore, consideration should be given to inseting the flap in such a way to alter the circular dimension of a resurfaced wound. For example, multiple Z-plasties involving the native skin and the flap skin can be performed to alter the contour of a circular wound.

INITIAL PATIENT AND WOUND CARE

The signature wound of the current United States military conflicts is that caused by blast and fragmentation.^{17,18} Projectile, thermal, and blast mechanisms combine to create wounds that are diffuse, heterogeneous, and extensive. It is common to have all tissue components of a limb affected. Not only are tissue planes dissected by the force of the blast, commonly there is projectile penetration across tissue planes far proximal to the foot and ankle, creating a large zone of injury with critical implications to reconstructive decision making.

The importance of aggressive, sharp débridement of traumatic wounds of all nonviable tissue is self-evident to the trained reconstructive surgeon. In contrast to lower-energy trauma prevalent in the United States civilian population, wherein only a few débridement procedures are generally necessary to render a wound clean and ready for reconstruction, the high-energy war wounds from the current United States military conflicts require an increased number of surgical débridement procedures, as these wounds are noted to devolve in the short term, somewhat analogous to burn wounds and frostbite. Indeed, a war wound that is aggressively debrided even by a seasoned military surgeon may appear alarmingly untidy several days later. Thus, when planning for definitive wound coverage of high-energy war wounds, the surgeon must be patient and prepared for an increased number of surgical débridement episodes.

Contrary to some surgeons' training, the authors typically use a tourniquet during the débridement of war wounds to minimize blood loss. Although use of a tourniquet obviously hinders the surgeon's ability to evaluate perfusion, it is often necessary to minimize the transfusion requirement in patients requiring multiple débridement procedures. At the conclusion of each débridement procedure, the tourniquet is released, viability of tissue assessed, and further débridement performed as needed.^{19,20}

The nutritional status of a trauma patient is critically important. The extensive nature of the wound burden results in high metabolic requirements. War-wounded patients are particularly vulnerable to nutritional deficiency for multiple reasons, despite their generally young and healthy state. During the 2- to 7-day evacuation out of the war zone, there are periods when nutritional needs are not emphasized due to numerous competing priorities. Multiple surgical episodes, sometimes daily or every other day for extended periods, are not uncommon in the early stages of care of the war wounded. Each of these may involve a prolonged antecedent period of nothing per mouth (NPO) as well as the commonly experienced delay in resuming a regular diet following anesthesia. These episodes

cumulatively have a negative impact on a patient's nutritional status. Prolonged mechanical ventilation and abdominal injuries are frequently concomitant with limb injuries and impair nutrition, even if tube feeding and peripheral nutrition are given.^{21,22}

Pulsatile lavage may be useful in initial débridement procedures to remove large particulate debris and foreign matter. However, repetitive use of pulsatile lavage is felt to be of limited value and there is evidence that it may even cause cumulative surface trauma, dissect tissue planes, and lead to a paradoxical rebound in the bacterial count of the wound. Further, the use of normal saline is preferred for irrigation solution, as there is evidence that additives, such as bacitracin, castile soap, and benzalkonium chloride, while reducing the bacterial load better than saline initially, result in a significant rebound in the bacterial count.²³ Low-pressure gravity flow irrigation of appropriate volumes of normal saline is recommended.

Granulation tissue is useful in that its appearance signals that a wound is capable of mounting a healing response on the local and systemic levels. However, it is largely unnecessary and undesirable with respect to flap coverage and ultimate function. Although granulation tissue is certainly a highly specialized tissue, it will not replace the sophisticated function of normal tissues such as bone, muscle, cartilage, ligament, tendon, or nerve. Granulation tissue cannot substitute for fascia, subcutaneous tissue, or dermis, as it is minimally elastic, does not epithelialize itself, and adheres to and tethers underlying structures, potentially causing functional impairment. Indeed, granulation tissue often only marginally accepts a split-thickness skin graft and becomes dense scar as it matures. Not infrequently the granulation response is so abundant that it protrudes through the slits in a meshed graft, causing a delay in full epithelialization. Granulation tissue can form on the surface of necrotic muscle, obscuring the true extent of injury; it also harbors bacteria. The authors typically debride all granulation tissue off of a wound bed at the time of flap coverage.

Perhaps the more difficult tasks of the microvascular surgeon occur before the actual flap procedure, in the form of critical decision making. The timing of the flap must be duly considered. Previous investigators have recommended that flap coverage occur within 72 hours of injury. In the authors' war-wounded population this is not a realistic possibility because of the logistical constraints of patient evacuation to a tertiary military facility in the United States capable of such procedures. The concept of early flap coverage has been challenged by numerous investigators, and successful delayed reconstructions have been reported with no apparent degradation of results.²⁴⁻²⁷ However, prospective studies on this subject are not available.

Before flap coverage, the wound must undergo sufficient to render it clean and stable (ie, not devolving as previously discussed). The patient must be physiologically stable, nutritionally optimized, and not require intensive interventions. Frequent transport to the imaging suite or operating room is undesirable, as this increases the risk of mechanically compromising the flap due to transfers, transports, and patient positioning. Intensive support with vasopressors, which will constrict blood vessels, precludes free tissue transfer. Careful consideration must be given to factors that may cause coagulopathy in the severely injured multitrauma patient due to the risk of hematoma, which can occlude the microvascular pedicle. Some war-wounded patients require more than one flap coverage procedure for separate wounds, which may make selection of the donor sites challenging. Furthermore, choice of donor sites may be affected by extensive concomitant injury. Close, frequent, efficient, and in-depth communication across surgical and medical specialties is critical to optimal care of the multitraumatized patient, particularly in institutions with high volumes of such patients.

SUBATMOSPHERIC WOUND DRESSING

The interim treatment of war wounds about the foot and ankle with subatmospheric wound dressing (SAWD) has many benefits.²⁸ However, its utility should not be misunderstood or overestimated. Without evacuation, excess wound exudate would cause tissue maceration and bacteria proliferation. A main feature of SAWD is the regular removal of wound exudate, including metalloproteinases that retard wound healing.²⁹ Yet SAWD prevents wound desiccation by serving as a vapor barrier. In addition, SAWD assists in reduction of wound edema, decreasing vascular compromise via reduction of interstitial pressure. Another significant benefit of SAWD is in the realm of improved morale for the patient and caretaker. Bulky, odorous gauze dressings are minimized and the frequency of dressing changes is much reduced, improving patient comfort and minimizing the workload of caretakers. The low-profile dressing allows the patient to inspect and more readily move his extremity, and also affords a better understanding of the nature of his wound and facilitates more effective participation in the recovery process. SAWD is an extremely effective antishear bolster dressing when applied over split-thickness skin grafts and engineered wound resurfacing products. However, SAWD will not clean, debride, or sterilize a wound, and may actually cause an increase in bacterial load compared with gauze dressing.^{30,31} The SAWD should not be placed over an actively infected wound until the infection is controlled. A SAWD that loses its seal creates a partially closed system conducive to bacterial overgrowth, a situation that should be remedied by removal or resealing as soon as it is identified. SAWD promotes granulation, which may be undesirable, as previously discussed.

Application of SAWD often needs to be creative, as the natural contours of the foot and ankle and the sharp, bulky components of an external fixator can make an airtight seal difficult to achieve. The sponge can be built on multidimensional wounds in a stepwise, piecemeal fashion to maximize contact of the sponge with the wound surface. A large adhesive film can be placed over the entire extremity and padded external fixator.³² Care must be taken to avoid losing bits of sponge in a wound that has many contours and crevices, or one that is granulating rapidly, as this can be a cause of foreign body reaction or infection.³³ The skin may need to be prepped or cleaned to facilitate a seal. Placement of SAWD over exposed or compromised vessels is not recommended.³⁴ Also, caution is recommended in placing the SAWD over free and rotational flaps, especially early in the course of the flap. Although the use of SAWD acutely over skin-grafted free tissue transfer has been reported,³⁵ the authors have encountered flap complications that they believe may have been caused by decreased tissue perfusion or compression of the vascular pedicle due to the bolster affect of SAWD.

SYNTHETIC DERMAL REPLACEMENT

The array of engineered resurfacing products for the management of wounds has expanded in recent years. The authors have had a favorable experience with Integra Dermal Regeneration Template (Integra Lifesciences, Plainsborough, NJ). This product is a bilayer dermal replacement system. The dermal replacement layer consists of a porous matrix of fibers of cross-linked bovine tendon collagen and a glycosaminoglycan (chondroitin-6-sulfate). The epidermal replacement layer is temporary and consists of a semiporous silicone. The dermal replacement layer serves as a matrix for the infiltration of fibroblasts, macrophages, lymphocytes, and capillaries. The silicone layer serves as a vapor barrier. Once the dermal replacement layer has adequately vascularized, the silicone layer is removed and a split-thickness skin graft is placed.

The indications for use of this product are still being explored, and are in evolution.^{36,37} The authors have noted several short- and long-term benefits to the product. The product is convenient in that it is stored at room temperature. Application is simple; it is trimmed to fit the dimensions of the wound and then stapled or sutured into place. On initial application of the product, SAWD can be employed as an antishear bolster directly over the silicone layer. The vapor barrier is extremely effective in keeping the wound moist, while allowing relatively painless and efficient wound care at the bedside as it does not adhere to gauze dressings. After typically 5 to 7 days the SAWD sponge is removed at the bedside. Shaving the skin surrounding the wound at the time of SAWD application facilitates its removal or exchange in the unanesthetized patient. The amount of drainage from the wound at this point is usually minimal. Through the silicone layer, the dermal replacement layer is inspected for adherence to the wound bed and progressive vascularization. Areas of nonadherence and exudate accumulation are treated with selective débridement. Multiple serial applications of Integra are occasionally performed to cover areas that have sloughed, required débridement due to infection, to build up additional thickness of replacement dermis over critical structures, or to improve the contour of the wound. The authors have found that a previously applied, adherent, and vascularized layer of Integra will readily accept additional layers of the product. A mature layer of Integra contains hues of yellow, orange, and red, and is smooth as it follows the contour of the wound bed. Of note, the cellular and vascular infiltration of the Integra matrix is not the same as granulation tissue and does not appear as such. The Integra seems to preclude the formation of granulation tissue on the wound bed. After 14 to 21 days, the site is surgically prepped directly over the silicone layer. The silicone is then removed and a split-thickness skin graft applied. Again, as an antishear bolster, a SAWD is used over the skin-grafted area. The surgeon can expect 100% skin graft results when conditions are optimized.

A mature wound that has been treated with Integra prior to skin grafting is more pliable and supple. The replacement dermis appears to develop some degree of differential excursion relative to the tissue underneath, improving wear characteristics. Indeed, the same product, minus the silicone layer, is marketed as Tenoglide (Integra Lifesciences, Plainsborough, NJ), and is recommended for layering around tendons to prevent scar adhesion and promote tendon gliding. Minimal or no wound contraction occurs, which is an important distinction to skin grafts placed directly over a wound bed. Integra can be placed selectively over avascular structures. When other means of wound coverage are not feasible, Integra can be used over tendon lacking paratenon, and bone lacking periosteum. The dermal replacement matrix will allow cellular and vascular infiltration at the periphery of the Integra where it overlaps vascular tissue. The vascular infiltration will then continue throughout the Integra layer to eventually form a complete bed suitable for skin grafting. When used for this purpose, multiple applications of Integra may be necessary. The use of Integra directly over open fractures is not recommended.

PEDICLED FLAPS

No microanastomosis is necessary for pedicled flaps, which can be a distinct advantage over free tissue transfer when there is an extensive zone of injury, as the recipient vessel of a free flap may be inflamed or damaged and prone to thrombosis. Of further potential benefit, as pedicled flaps are usually based on collateral branches of main vascular axes, no major vessels need be sacrificed, as opposed to free tissue transfer to the foot and ankle where end-to-end anastomoses to a main vessel may be necessary.³⁸

The authors have experience with the distally based sural neurofasciocutaneous pedicled flap, the distally based lateral supramalleolar fasciocutaneous pedicled flap, the extensor digitorum brevis muscle pedicled flap, and the abductor hallucis muscle pedicled flap.

Distally Based Sural Neurofasciocutaneous Pedicled Flap

The use of the distally based sural neurofasciocutaneous pedicled flap has expanded dramatically in recent years.^{39,40} This flap is raised as a fasciocutaneous flap on the posterior aspect of the leg, and is suitable for covering defects about the ankle joint, the heel, and the dorsum of the foot (Fig. 3). The vascular inflow of the flap is provided by retrograde flow through the sural artery, which courses with the sural nerve. Outflow is via venae comitantes. The sural nerve pierces the deep fascia of the leg between the 2 heads of the gastrocnemius and then courses distally and laterally to a position just posterior to the lateral malleolus. The flap provides sensation to the lateral aspect of the hindfoot. In general the patient easily accepts the loss of sensation caused by the division of the sural nerve, necessary in raising this flap. The sural artery has numerous anastomoses with the peroneal artery in the distal leg. The pivot point of the pedicled flap should occur not less than 5 cm superior to the lateral malleolus to preserve communicating vessels between the sural and peroneal arteries. Patency of the sural artery can be determined preoperatively at the bedside with a handheld Doppler. With alternating finger pressure proximally and distally along the sural nerve, the patency of the distal communicating vessels can be determined with a Doppler ultrasound sensor.

The authors have raised flaps measuring up to 9 cm in width and 22 cm in length without flap necrosis. Any flap greater than 6 cm in width will likely require skin grafting of the donor site. Primary closure of the donor site must proceed with caution irrespective of flap size, as compartment syndrome and venous outflow compromise are real concerns. The surgeon must be aware of the negative effect on the integument of raising the sural neurofasciocutaneous flap with respect to the potential future need to perform a transtibial amputation. When marking the skin for the flap, the point at which the medial and lateral heads of the gastrocnemius diverge is noted, and not more than one-third of the flap is raised proximal to this level because the blood supply superior to this point is expected to be random-pattern flow (Fig. 4). From the distal tip of the flap to the point of pedicle rotation, the skin is incised just through the dermis. The dermis is reflected without disturbing the fat and fascia for 1 cm on either side of the expected location of the sural nerve and artery. Thus, a breadth of 2 cm of fat and fascia is incorporated around the pedicle and raised as a leash. The flap itself is raised on this leash by incising through fat and fascia and raising the flap off of the underlying muscle. The sural artery and nerve, and the short saphenous vein are located as they pierce the fascia, and are ligated proximally. The sural nerve should be dissected and truncated proximally so the neuroma that forms is located deep under muscle. The fasciocutaneous flap and its vascular leash are then mobilized, reflected distally, and inset (Figs. 5 and 6).

The pedicle can be tunneled under an intact bridge of skin, but great care must be taken when this is done to ensure that it is not constricted, particularly given the tendency for venous congestion in reverse-flow flaps.⁴¹ The authors prefer to exteriorize the pedicle by incising and lifting the skin edges along the course of the pedicle, then placing pedicle in this wound with the skin edges loosely draped over it. Because the pedicle is raised with a cuff of fascia and fat, the artery and vein are protected from desiccation. Further measures should be employed, however, to protect the exposed pedicle, such as moisture-retaining dressings or a dermal replacement product. Immediate skin grafting of the pedicle can be done, but the success of this is variable, as the skin graft may take poorly to the fat and fascia surrounding the pedicle. An anti-shear bolster should not be used due to the potential for compressing the pedicle. In general the authors have delayed skin grafting of the exteriorized pedicle until it develops granulation tissue. Alternatively, after sufficient healing of the flap has occurred, the exteriorized pedicle can be excised and the wound closure modified, as the flap will have gained collateral flow from the skin margins and wound bed. Care must be taken in using this flap in older individuals, in patients with

diabetes and peripheral artery disease, and in smokers, as there is a higher complication rate in these groups. Consideration can be given to staging the flap by first incising the margins in the first stage, followed by developing the pedicle and inseting the flap in a second stage. This process is thought to minimize critical ischemia of the flap by allowing for tissue perfusion to adjust over time.⁴²

Lateral Supramalleolar Fasciocutaneous Pedicled Flap

The lateral supramalleolar fasciocutaneous pedicled flap has been used much less frequently than the sural artery fasciocutaneous pedicled flap.^{39,43} This flap is a distally based fasciocutaneous flap harvested from the lateral aspect of the lower leg. The flap may be chosen over the sural neurofasciocutaneous flap when the skin of the posterior leg is affected and would not permit a sural neurofasciocutaneous flap, or when the blood supply of the sural neurofasciocutaneous flap may be compromised due to local trauma. This flap has the advantage over the sural neurofasciocutaneous flap of reaching more distal on the foot. In general, but not absolutely, the distal sensory component of the superficial peroneal nerve must be divided when raising the flap. When divided, the proximal stump of the nerve should be buried in muscle to minimize the complication of painful neuroma.

The vascular supply of this flap is based on vessels of the anastomotic arcade of the ankle. The anastomotic arcade is developed from a perforating branch of the peroneal artery that courses through the interosseous space about 5 cm proximal to the lateral malleolus, the anterior lateral malleolar artery that arises from the anterior tibial artery, and by ascending branches from the lateral tarsal artery (Fig. 7). Outflow is supplied via venae comitantes.

Soon after piercing the interosseous membrane, the perforating branch of the peroneal artery gives off 1 or 2 branches to the skin of the lateral leg before joining in the anastomotic arcade of the ankle. These branches to the skin are the basis of the flap. The flap can be pivoted off of the perforating branch of the peroneal artery if a long pedicle is not needed. As an alternative, the perforating branch of the peroneal artery can be divided proximal to the skin branches and the anterior lateral malleolar artery can be used as the inflow of the flap. If even more pedicle length is required, then both the perforating branch of the peroneal artery and the anterior lateral malleolar artery can be divided in the appropriate locations, and the anastomotic arcade can be carefully dissected and elevated down to the lateral tarsal artery (Fig. 8). The key is to preserve the skin branches and to accommodate for variability in individual vascular anatomy as it is dissected, to ensure inflow from one of these branches of the arcade. A cuff of adipofascial tissue should be raised with the pedicle to protect the artery and venous outflow. The pedicle does course deep to the extensor retinaculum, which must be incised when harvesting this flap.

Extensor Digitorum Muscle Pedicled Flap

The extensor digitorum muscle pedicled flap has limited indications and has limited use for the coverage of war wounds, largely because of frequent extensive tissue involvement in the area.^{39,44,45} The extensor digitorum flap is a small muscle, measuring approximately 4.5 by 6.0 cm, whose harvest leaves minimal morbidity. The flap can be useful for coverage of the perimalleolar area, the dorsum of the foot, and the metatarsal phalangeal joints. The main vascular supply of the flap is the lateral tarsal artery, which is a branch off of the anterior tibial artery. The dorsalis pedis artery is the continuation of the anterior tibial artery after the branching of the lateral tarsal artery (Fig. 9). The flap can be pedicled on the anterior tibial artery as an antegrade-flow flap, or the dorsalis pedis artery as a retrograde-flow flap, depending on the location of the wound. Using the anterior tibial artery as the pedicle will afford a long pedicle with reach proximal to the normal level of the muscle, while using the dorsalis pedis artery and retrograde flow the flap will reach distally to the toes. Or, if only a

short pedicle is needed, the anterior tibial/dorsalis pedis arterial axis need not be divided, and the flap can simply be rotated on the lateral tarsal artery. This procedure is generally only applicable for anterior or medial ankle wounds. Before dividing the anterior tibial/dorsalis pedis arterial axis, the surgeon must ensure that the vascularity of the foot will not be compromised. When raising the flap, care should be taken to avoid disturbing the paratenon covering the long toe extensors, as these tendons must be mobilized to access the muscle. The flap is not harvested with skin; therefore, the wound can be directly closed without the need for skin grafting.

Abductor Hallucis Muscle Pedicled Flap

The proximally based abductor hallucis muscle pedicled flap has limited use for coverage of medial hindfoot defects.^{39,46} This flap is not mobile enough to reliably cover defects of the medial ankle or medial malleolar area. As with the extensor digitorum muscle pedicled flap, the abductor hallucis muscle pedicled flap has been uncommonly used by the authors for the coverage of war wounds, due to the generally extensive nature of these wounds. The blood supply of the flap is derived from numerous branches from the medial plantar artery as it courses underneath the muscle (Fig. 10). The medial plantar artery can be preserved and the muscle mobilized from distal to proximal by progressive ligation of the perforating arteries. This ligation may cause the distal portion of the muscle to become ischemic. Alternatively, the medial plantar artery can be ligated distally and mobilized with the muscle, providing a more robust blood supply. In practice, even if the medial plantar artery is sacrificed distally and reflected with the muscle, the pedicle length is not dramatically improved because the medial plantar artery is rather short as it branches from the posterior tibial artery. Further proximal dissection of the pedicle to include the posterior tibial artery would require ligation of both the medial and lateral plantar arteries, which would severely compromise the blood supply to the foot.

FREE TISSUE TRANSFER

Free tissue transfer is a powerful tool for the reconstructive surgeon, but it has limitations. Free tissue transfer affords the opportunity to recruit uninjured specialized tissues into a wound not only to provide coverage but also potentially to return function. This procedure requires an extensive team of specially trained surgeons, nurses, technicians, and a complement of costly, specialized equipment.^{11,47,48} The key to success of free tissue transfer is the placement of multiple lumen-inverting sutures to oppose endothelium and exclude from the anastomosis local thromboinductive tissue, namely the adventitia. Trauma to the endothelium during the microsurgical anastomosis must be avoided, and endothelium with preexisting injury due to the war injury must be excluded.

The site of anastomosis should ideally be entirely free of trauma and inflammation. As previously discussed, very often the zone of injury extends well into the leg and even the thigh. In such cases, free tissue transfer may be considered too risky and thus abandoned in favor of another form of wound management. Plain films should be scrutinized for evidence of deep penetration of debris far beyond the foot and ankle even when only relatively minor skin wounds are found on examination. The authors routinely use computerized tomographic angiography (CTA) to determine whether potential recipient vessels have sustained trauma. On several occasions, the site of microanastomosis was changed or free tissue transfer was not performed, due to the discovery of vessel injury on CTA. End-to-side arterial anastomosis is performed when possible to avoid sacrificing a main artery. However, end-to-end anastomosis is chosen if the recipient artery is small and the vascular status of the foot is such that sacrificing a main artery would not be too detrimental.

As the patient is brought into the room and positioned, 300 mg of aspirin is given per rectum. Postoperatively it is continued orally at 325 mg daily for 1 month. Detailed attention is given to patient positioning. Harvesting and inseting the flap at the recipient site is typically time consuming, requiring the patient be protected from accidental vessel, nerve, and skin compression. Arterial monitoring is often performed by the anesthesia provider. If this is done before arrival in the operating room, time is saved. The patient arrives in the operating room hemodynamically optimized, but is typed and cross-matched for possible transfusion. Due to the need for access to the donor and recipient sites, the patient may remain very exposed after prepping and draping. Therefore, arranging blanket and warmer cover for the patient without compromising the surgical fields is very important. The table and patient are positioned with thought to where the microscope will be brought in and to where 2 microsurgeons will operate. The surgeons should be in a comfortable sitting position; rarely the microvascular anastomosis must be done with the surgeons standing. The patient's position may be reversed on the operating table to prevent the main post from interfering with the surgeons' legs. Prophylactic antibiotics are given at the beginning of the procedure and at routine intervals thereafter. The operating room personnel ideally are familiar with the technique and requirements of performing microvascular free flaps. This knowledge includes the ability to prepare the necessary instruments, equipment, and fluids so that they are readily available when needed. If a monitor is available to connect to the microscope, all individuals in the room may observe the microscopic part of the case, which will allow them to anticipate needs and avoid inefficiency resulting from boredom and distraction.

Two surgical teams with 2 trained and credentialed microsurgeons are preferred, not only to minimize surgical time for the patient but also to minimize surgeon fatigue. This teamwork is particularly important in facilities that perform high volumes of free tissue transfers. While the donor site is dissected, any preliminary surgery on the recipient site is performed, such as final débridement, bone stabilization, and preparation of the recipient vessels. After the flap is fully mobilized but the pedicle has not yet been divided, and preliminary recipient site preparation has been performed, the 2 surgical teams each take staggered breaks as needed. During this time the remaining team can complete irrigation and débridement, set up the microscope and the microscopic field, further prepare the recipient vessels, and begin closing the donor site. Several minutes before division of the flap pedicle at the donor site, approximately 5000 units of heparin are given intravenously, adjusted according to patient size and weight.

The authors have begun using a continuous tissue oxygenation monitoring system for monitoring the flap post surgery (ViOptix Tissue Oximeter, ViOptix Inc, Fremont, CA). Use of this device entails affixing a sterile probe to a skin paddle of the flap and connecting the probe to a monitor. The monitor measures tissue oxygenation continuously, and provides a constant display of absolute value as well as a running time-based graph. The device is extremely helpful in giving early warning of flap compromise, long before a problem is detected by change in color, temperature, or Doppler signal; its use expedites operative exploration and correction of the problem. In addition to postoperative monitoring, the tissue oxygenation monitor is used during the surgical procedure to give real-time information about the status of the flap during harvest and inset. A baseline tissue oxygenation level is determined after completely mobilizing the flap from the donor site and isolating the pedicle, but before division of the pedicle. This value sets the expectation for tissue oxygenation once the anastomosis is completed. Inadvertent compromise of tissue oxygenation during inseting of the flap and closure of the wound over the pedicle can be immediately identified and addressed.^{49,50} For muscle flaps, inclusion of a skin paddle is necessary for use of this monitoring device.

After free-tissue transfer, the patient is monitored hourly in the intensive care unit. The tissue monitor and hourly checks are maintained for at least 4 days. If external skeletal fixation is applied, balanced suspension is frequently used to elevate the extremity just above heart level. Balanced suspension is advantageous because it allows the patient to reposition his leg and whole body with minimal effort, as the weight of the leg is counterbalanced. A warming blanket set at medium-high temperature is applied to the extremity to promote vasodilation. The room temperature is set per patient comfort. Intake of nicotine (all tobacco products as well as nicotine patches), caffeine, and chocolate are forbidden due to their vasoconstrictive properties. However, the scientific literature provides strong recommendations only for nicotine.⁵¹ Hemoglobin levels are maintained to prevent signs and symptoms of anemia. In case emergent flap exploration is needed, the patient is kept NPO on the first postoperative day, as most cases of flap compromise occur in the first 24 hours post anastomosis. Following this a supplemented regular diet is resumed as soon as possible. In addition to daily aspirin, anticoagulation therapy is administered when indicated for prophylaxis against deep venous thrombosis. Intravenous heparin and Dextran 40 are not routinely given in the postoperative period.

Any sign of vascular compromise is addressed aggressively, with a very low threshold for emergent operative exploration. Bedside troubleshooting is done to rule out faulty monitoring equipment, constrictive dressings, a clogged drain, and compromised limb position; if present these issues are addressed. The operating room is notified and instructed to prepare for the case as if an entirely new flap were to be performed. While operative exploration is arranged, consideration should be given to releasing skin sutures if it is suspected that the skin itself or a wound hematoma is compressing the pedicle. Once in the operating room, the artery and vein are inspected, and the problem is identified and remediated. Although time is of the essence, the microsurgeon must carefully and methodically identify and correct all problems. If needed, all anastomoses are taken down, previously sewn vessels are trimmed to fresh tissue, and the microanastomoses are redone, using vein grafts if needed.

In cases of significant venous congestion, the thrombolytic agent alteplase has been focally infused into the arterial system of the flap (1 mg/5 mL for a total of 3–5 mg) at the time of operative exploration. This infusion has been done only when restoration of adequate venous return is not achieved after its root cause has been identified and corrected. If possible, the alteplase is infused through a side branch of the arterial pedicle, without taking down the anastomosis if it is otherwise pristine and patent.⁵² Medicinal leeches have been extremely valuable in treating certain cases of venous congestion of free and pedicled flaps.^{53,54} However, leeches are used in addition to operative exploration. Leeches are only recommended for small flaps. On occasion, a small Fogarty catheter may be used to extract a clot from some flaps; this should be done judiciously to prevent intimal damage to the vessels, which would promote repeat thrombosis.

Below the authors review flaps they have commonly used in free-tissue reconstruction of war wounds to the foot and ankle. Most frequently the authors have used the anterolateral thigh free flap. Other flaps commonly used have included the rectus abdominis muscle free flap and the latissimus dorsi muscle free flap. The authors have not used the lateral arm free flap, the radial forearm free flap, or the gracilis muscle free flap for reconstruction of the foot and ankle due to their satisfaction and experience with the aforementioned. However, these latter flaps are described, and should be considered according to the individual circumstances of the patient and the experience of the surgeon.

Anterolateral Thigh Free Flap

The use of the anterolateral thigh free flap has increased dramatically in recent years due to its recognized reliability, potential size, relative ease of harvesting, and minimal donor morbidity.^{55,56} Harvesting the flap with the patient in the supine position is an attractive feature of this flap that must not be underappreciated, particularly in the multiply injured war-wounded patient. Although it can become rather thick in obese individuals, this flap generally provides a pliable source of fascia and skin, with a vascular pedicle of 10 to 13 cm in length and up to 2 to 3 mm diameter. Especially in men, it can be quite pileous. The size of this flap can be very large, up to 15 cm in width and 25 cm in length. Primary closure of the donor site is usually possible with flap width up to 8 cm.

The anterolateral thigh free flap is based on a myocutaneous perforator through the vastus lateralis muscle in 84% of cases. Otherwise it is based on a septocutaneous perforator coursing between the vastus lateralis and the rectus femoris muscles. The perforator vessel or vessels generally derive from the descending branch of the lateral circumflex femoral artery, which courses between the vastus lateralis and the rectus femoris, or from a direct branch of the lateral circumflex femoral artery distinct from the descending branch (Fig. 11). Branches of the femoral nerve will be encountered when raising this flap and should be preserved. A portion of the vastus lateralis can be harvested with this flap for use in filling a wound cavity. Although anatomic variation in the anatomy of the skin perforators can make the harvesting of the flap tedious and stressful, experience has demonstrated that the patient surgeon can expect a satisfactory pedicle. Before circumferentially raising the flap, however, the presence of an arterial perforator must be absolutely confirmed.⁵⁷ The authors always counsel the patient that both thighs may have to be explored for an acceptable flap, but have not as yet had to resort to this. Care must be taken when dissecting the pedicle to avoid muscular branches of the femoral nerve. When combined with a strip of the fascia lata, an Achilles tendon can be reconstructed. A sensate flap can be made by including the anterior branch of the lateral femoral cutaneous nerve and suturing this to a sensory nerve at the recipient site (Figs. 12 and 13).

Latissimus Dorsi Muscle Free Flap

The latissimus dorsi muscle free flap is a predictable, reliable, and adaptable option for the reconstructive surgeon.^{55,58} This flap is large and is relatively easy to harvest with predictable, large diameter vessels. The flap is based on the thoracodorsal artery, which is a branch of the subscapular artery, and has a length of 6.0 to 11.5 cm from its branch-off of the subscapular artery to its entrance into the muscle (Fig. 14). The thoracodorsal is a large artery that has only one large vena comitans. Immediately on entering the muscle, it splits into medial and lateral branches. The flap can be made bilobed, based on the medial and lateral branches of the thoracodorsal artery, augmenting its ability to resurface complex wounds. The thoracodorsal nerve travels with the artery and vein, and must be dissected and ligated, unless only a partial flap is raised and some residual functional muscle is intended. In its course the thoracodorsal artery typically gives rise to 2 arteries, which must be ligated: the angular artery to the lateral border of the scapula and a branch to the serratus anterior muscle. There is some variability in the origin of these arteries, however. The entire muscle typically will survive off of the thoracodorsal artery and vena comitans. However, the distal margins of the flap are also supplied segmentally by intercostals and lumbar arteries, and occasionally necrosis of the distal edges of the flap occurs.

Patients have minimal deficit after harvesting of the latissimus dorsi because of the compensatory action of adjacent muscles; namely, the pectoralis major and the teres major. The latissimus dorsi muscle itself can measure up to 40 cm in length and 20 cm in width, and have a thickness of about 0.8 cm. Combining the length of the pedicle and the length of

the muscle itself, the overall reach of the latissimus dorsi muscle free flap can be over 40 cm, which can be a distinct benefit when a wide zone of injury needs to be traversed to obtain coverage of a foot and ankle. A skin paddle up to 20 cm in width and 40 cm in length can be raised with the muscle. Any skin paddle wider than 10 cm will likely need secondary skin grafting of the donor site. The skin paddle will have significant excursion and mobility relative to the underlying latissimus muscle, which may result in ulceration with shoe wear and if it is used on weight-bearing surfaces. Furthermore, because of its multisegmental cutaneous sensory innervation, it is not possible to obtain sensate coverage with this flap. Also, the adipose layer is often thick in this area, and results in a bulky flap. If such circumstances are a concern, then a split- or full-thickness skin graft placed over the muscle may be a better, more durable choice than lifting a skin paddle with the graft. However, even if later excised and skin grafted, a small skin paddle can be lifted with the muscle flap for the purpose of flap monitoring, as it is simpler to monitor a skin paddle than muscle.

To avoid a skin contracture across the shoulder joint, the surgeon should not incise into the axillary skin. The pedicle may be developed by elevating and dissecting under the axillary skin. If an incision into the axillary skin is necessary to safely develop the pedicle, a zig-zag incision is recommended. Two to 3 large round drains are placed in the harvest site, sutured to the skin, and placed on bulb suction. To minimize seroma formation at the donor site, the drains are kept in place until the drainage is less than 10 mL per 8-hour shift per drain for 4 consecutive shifts.

A relative drawback of the latissimus dorsi muscle free flap is the challenge that arises in patient positioning for the procedure. The patient must be positioned in such a way to permit a technically sound microvascular anastomosis. This procedure must be accomplished without sacrificing access to the recipient wound so the flap can be properly inset. Both of these need to be performed while placing the patient in as close as possible to a lateral decubitus or prone position to allow harvesting of the latissimus flap. The surgeon should also consider that the lateral decubitus position may be physiologically disadvantageous in the multi-injured patient.

Rectus Abdominis Muscle Free Flap

The rectus abdominis muscle free flap is also a reliable and predictable flap.^{55,59} Either the deep superior or deep inferior epigastric artery can be used to supply the free tissue transfer. The deep inferior epigastric artery, arising from the external iliac artery, is generally chosen for free-tissue transfer because it is larger and longer, and it provides a more favorable network of perforators to the skin, should a myocutaneous flap be fashioned. The deep inferior epigastric artery provides a pedicle length ranging from 7.1 to 14.7 cm and its diameter is approximately 2 mm (Fig. 15). This artery has 2 venae comitantes. Just as the latissimus dorsi myocutaneous flap has multisegmental cutaneous sensory innervation, the skin over the rectus musculature is segmentally innervated by the intercostal nerves. However, it also has segmental motor innervation so the flap can neither maintain motor function nor be sensate. The average dimensions of this flap are 30 cm in length, 6 cm in width, and 0.6 cm in thickness. The dimensions of this flap have obvious implications with respect to utility compared with the latissimus dorsi muscle flap. The effective reach of the flap is sizeable, yet not as great as the latissimus dorsi muscle flap. If great length is needed to reach a site of microanastomosis out of the zone of injury, either the latissimus dorsi muscle free flap or the rectus abdominis muscle free flap may satisfy. However, when there is a large zone of injury that must be spanned, yet the remote wound is relatively small, then the breadth of tissue supplied to the target by the latissimus dorsi muscle free flap may be more than needed; in these cases the rectus abdominis muscle free flap may be more suitable.

The function of the rectus abdominis musculature is to flex the vertebral column and to supply strength to the abdominal wall. Morbidities of harvesting this muscle are potential weakness of trunk flexion and abdominal herniation. The patient frequently has significant reservations to the procedure because of the misperception that a cosmetic deficit of losing “half of their 6-pack abs” will result. A significant relative advantage of the flap is the ease of patient positioning and harvesting.

CROSS-LEG COVERAGE

The aforementioned pedicled and free flaps have served as the authors’ predominant reconstructive choices for complex war wounds to the foot and ankle. Size and location of the defect and an expansive local zone of injury involving the proposed donor tissues may preclude coverage by local pedicled or rotational flaps. Technical limitations or lack of an adequate recipient vessel may prevent successful microsurgical free tissue transfer. Cross-leg and cross-foot flaps may be considered as an alternative in such circumstances.

Conventional cross-leg flaps were either random-pattern flaps or axial flaps based on the main axial vessel of the leg. These flaps have limited dimensions and arc of rotation. The pedicles are short, thick, and not capable of being stretched. The authors’ preference has been to use perforator-perfused cross-leg fasciocutaneous flaps. These flaps can be raised off the sural, posterior tibial, and peroneal artery perforators. Successful coverage of the entire plantar surface (21 × 11 cm) has been described, raising a flap from the proximal calf.⁶⁰ Most commonly the authors have used the sural fasciocutaneous flap, as described earlier. These flaps can be developed with a relatively long and narrow pedicle, which allows for greater excursion and arc of rotation; this facilitates coverage of larger and more distal defects, and may prevent the need for rigid cross-legging with external fixation in appropriate situations. The pedicle can reliably be divided and inset at 3 weeks.

A cross-leg, instep, plantar medial fasciocutaneous flap has also been described to provide durable glabrous skin coverage to smaller weight-bearing calcaneal and forefoot defects. This flap should be raised from a plane just superficial to the plantar fascia to create a thinner flap and decrease morbidity to the donor foot.⁶¹ After ligation of the lateral plantar artery and calcaneal branches distal to the perforator origin, the flap is tunneled under the abductor hallucis muscle without releasing it. The pedicle is then dissected proximally along the posterior tibial vessels. If a healthy recipient neural stump is present, consideration may be given to include the medial plantar nerve in the flap dissection and to attempt neural coaptation. Before inseting, the legs are appropriately positioned and immobilized with external fixation. A split-thickness skin graft may be wrapped without tension around the pedicle. Pedicle division occurs at 3 weeks.

Cross-leg *free* flaps provide one final option in the management of the most severe lower extremity wounds in specific circumstances. The success of free flap reconstruction depends to a large extent on the presence of healthy recipient vessels with adequate caliber for microanastomosis. Such specific circumstances include those in which no suitable recipient vessels exist in proximity to the defect and thicker muscle coverage is favored over a perforator-perfused cross-leg fasciocutaneous flap. In these cases, the vascular pedicle of a free muscle flap can be temporarily anastomosed to the recipient vessels in the contralateral leg and then divided after adequate neovascularization of the flap is established from the recipient bed.⁶² Positioning of the legs and protection of the pedicle from desiccation are of critical importance. Flap division is usually performed at 4 weeks for a myocutaneous flap. Various donor options have been reported including an iliac osteocutaneous, fibular osteomyocutaneous, tensor fascia lata myocutaneous, latissimus dorsi muscle, rectus abdominis muscle, and parascapular skin flaps. The authors have not had significant

experience with this technique. Preoperative joint stiffness preventing appropriate positioning without undue tension on the flap pedicle is a contraindication to these cross-leg procedures. As such, postoperative physical therapy following flap division is essential to prevent the development of joint contractures.

SUMMARY

Reconstruction of the war-wounded foot and ankle is a challenging process requiring endurance, patience, diligence, and many harrowing decisions for the patient and surgeon. These decisions involve reconciling the difficult balance between expectations and feasibility. The reconstructive process does not end with the successful healing of a flap. Indeed, the surgeon must counsel the patient that flap coverage is but one small component of the reconstruction process. Multiple procedures may be necessary before the patient reaches maximum function. Over time, the patient and the surgeon may consider revisions of a flap to improve shoe wear and weight-bearing of the reconstructed foot and ankle. Also of high importance is the availability of a skilled orthotist for custom fitting of braces and shoe wear in the post-reconstructive period. Ultimately, the patient is the final judge of the outcome of foot and ankle reconstruction. It is not a rare occurrence that the patient and surgeon agree at some point during reconstructive efforts that an amputation is the best option.

References

1. Potter BK, Scoville CR. Amputation is not isolated: an overview of the US Army Amputee Patient Care Program and associated amputee injuries. *J Am Acad Orthop Surg.* 2006; 14(10 Spec No):S188–90. [PubMed: 17003197]
2. Kumar AR, Grewal NS, Chung TL, et al. Lessons from operation Iraqi freedom: successful subacute reconstruction of complex lower extremity battle injuries. *Plast Reconstr Surg.* 2009; 123(1):218–29. [PubMed: 19116556]
3. Keeling JJ, Gwinn DE, Tintle SM, et al. Short-term outcomes of severe open wartime tibial fractures treated with ring external fixation. *J Bone Joint Surg Am.* 2008; 90(12):2643–51. [PubMed: 19047709]
4. Leininger BE, Rasmussen TE, Smith DL, et al. Experience with wound VAC and delayed primary closure of contaminated soft tissue injuries in Iraq. *J Trauma.* 2006; 61(5):1207–11. [PubMed: 17099530]
5. Beardmore AA, Brooks DE, Wenke JC, et al. Effectiveness of local antibiotic delivery with an osteoinductive and osteoconductive bone-graft substitute. *J Bone Joint Surg Am.* 2005; 87(1):107–12. [PubMed: 15634820]
6. Brooks DE, Bice TG, et al. Tobramycin-impregnated calcium sulfate prevents infection in contaminated wounds. *Clin Orthop Relat Res.* 2005; 441:366–71. [PubMed: 16331028]
7. Zalavras CG, Patzakis MJ, Holtom P. Local antibiotic therapy in the treatment of open fractures and osteomyelitis. *Clin Orthop Relat Res.* 2004; 427:86–93. [PubMed: 15552142]
8. Russell RC, Guy RJ, Zook EG, et al. Extremity reconstruction using the free deltoid flap. *Plast Reconstr Surg.* 1985; 76(4):586–95. [PubMed: 2863835]
9. Katsaros J, Schusterman M, Beppu M, et al. The lateral upper arm flap: anatomy and clinical applications. *Ann Plast Surg.* 1984; 12(6):489–500. [PubMed: 6465806]
10. Santanelli F, Tenna S, Pace A, et al. Free flap reconstruction of the sole of the foot with or without sensory nerve coaptation. *Plast Reconstr Surg.* 2002; 109(7):2314–22. [discussion: 2323–4]. [PubMed: 12045556]
11. Baumeister S, Germann G. Soft tissue coverage of the extremely traumatized foot and ankle. *Foot Ankle Clin.* 2001; 6(4):867–903. ix. [PubMed: 12134586]
12. May JW Jr, Halls MJ, Simon SR. Free microvascular muscle flaps with skin graft reconstruction of extensive defects of the foot: a clinical and gait analysis study. *Plast Reconstr Surg.* 1985; 75(5): 627–41. [PubMed: 2858896]

13. Sommerlad BC, McGrouther DA. Resurfacing the sole: long-term follow-up and comparison of techniques. *Br J Plast Surg*. 1978; 31(2):107–16. [PubMed: 638300]
14. Stevenson TR, Mathes SJ. Management of foot injuries with free-muscle flaps. *Plast Reconstr Surg*. 1986; 78(5):665–71. [PubMed: 2876448]
15. Rautio J. Resurfacing and sensory recovery of the sole. *Clin Plast Surg*. 1991; 18(3):615–26. [PubMed: 1889171]
16. Chang KN, DeArmond SJ, Buncke HJ Jr. Sensory reinnervation in microsurgical reconstruction of the heel. *Plast Reconstr Surg*. 1986; 78(5):652–64. [PubMed: 3763751]
17. Owens BD, Kragh JF Jr, Wenke JC, et al. Combat wounds in operation Iraqi Freedom and operation Enduring Freedom. *J Trauma*. 2008; 64(2):295–9. [PubMed: 18301189]
18. Owens BD, Kragh JF Jr, Macaitis J, et al. Characterization of extremity wounds in Operation Iraqi Freedom and Operation Enduring Freedom. *J Orthop Trauma*. 2007; 21(4):254–7. [PubMed: 17414553]
19. Smoot EC 3rd. Modified use of extremity tourniquets for burn wound debridement. *J Burn Care Rehabil*. 1996; 17(4):334–7. [PubMed: 8844354]
20. O'Mara MS, Goel A, Recio P, et al. The use of tourniquets in the excision of unexsanguinated extremity burn wounds. *Burns*. 2002; 28(7):684–7. [PubMed: 12417166]
21. McCarthy MS, Fabling J, Martindale R, et al. Nutrition support of the traumatically injured warfighter. *Crit Care Nurs Clin North Am*. 2008; 20(1):59–65. vi–vii. [PubMed: 18206585]
22. Fang R, Pruitt VM, Dorlac GR, et al. Critical care at Landstuhl Regional Medical Center. *Crit Care Med*. 2008; 36(Suppl 7):S383–7. [PubMed: 18594267]
23. Owens BD, White DW, Wenke JC. Comparison of irrigation solutions and devices in a contaminated musculoskeletal wound survival model. *J Bone Joint Surg Am*. 2009; 91(1):92–8. [PubMed: 19122083]
24. Sherman R, Rahban S, Pollak AN. Timing of wound coverage in extremity war injuries. *J Am Acad Orthop Surg*. 2006; 14(10 Spec No):S57–61. [PubMed: 17003209]
25. Karanas YL, Nigriny J, Chang J. The timing of microsurgical reconstruction in lower extremity trauma. *Microsurgery*. 2008; 28(8):632–4. [PubMed: 18846574]
26. Steiert AE, Gohritz A, Schreiber TC, et al. Delayed flap coverage of open extremity fractures after previous vacuum-assisted closure (VAC) therapy—worse or worth? *J Plast Reconstr Aesthet Surg*. 2009; 62(5):675–83. [Epub 2008 Mar 25]. [PubMed: 18373969]
27. Levin LS. Early versus delayed closure of open fractures. *Injury*. 2007; 38(8):896–9. [Epub 2007 Jun 21]. [PubMed: 17585912]
28. Geiger S, McCormick F, Chou R, et al. War wounds: lessons learned from Operation Iraqi Freedom. *Plast Reconstr Surg*. 2008; 122(1):146–53. [PubMed: 18594399]
29. Greene AK, Puder M, Roy R, et al. Microdeformational wound therapy: effects on angiogenesis and matrix metalloproteinases in chronic wounds of 3 debilitated patients. *Ann Plast Surg*. 2006; 56(4):418–22. [PubMed: 16557076]
30. Mouës CM, Vos MC, van den Bemd GJ, et al. Bacterial load in relation to vacuum-assisted closure wound therapy: a prospective randomized trial. *Wound Repair Regen*. 2004; 12(1):11–7. [PubMed: 14974959]
31. Weed T, Ratliff C, Drake DB. Quantifying bacterial bioburden during negative pressure wound therapy: does the wound VAC enhance bacterial clearance? *Ann Plast Surg*. 2004; 52(3):276–9. [discussion: 279–80]. [PubMed: 15156981]
32. Ozer K, Smith W. A simple technique for applying vacuum-assisted closure therapy over the circular type external fixation device. *Ann Plast Surg*. 2006; 56(6):693–4. [PubMed: 16721088]
33. Saeed MU, Kennedy DJ. A retained sponge is a complication of vacuum-assisted closure therapy. *Int J Low Extrem Wounds*. 2008; 7(1):51. [PubMed: 18372273]
34. Bluman EM, Hills C, Keeling JJ, et al. Augmented subatmospheric wound dressings (SAWDA): technique tip. *Foot Ankle Int*. 2009; 30(1):62–4. [PubMed: 19176188]
35. Hanasono MM, Skoracki RJ. Securing skin grafts to microvascular free flaps using the vacuum-assisted closure (VAC) device. *Ann Plast Surg*. 2007; 58(5):573–6. [PubMed: 17452846]

36. Jeng JC, Fidler PE, Sokolich JC, et al. Seven years' experience with Integra as a reconstructive tool. *J Burn Care Res.* 2007; 28(1):120–6. [PubMed: 17211211]
37. Helgeson MD, Potter BK, Evans KN, et al. Bioartificial dermal substitute: a preliminary report on its use for the management of complex combat-related soft tissue wounds. *J Orthop Trauma.* 2007; 21(6):394–9. [PubMed: 17620998]
38. Rooks MD. Coverage problems of the foot and ankle. *Orthop Clin North Am.* 1989; 20(4):723–36. [PubMed: 2797760]
39. Masquelet, AC.; Gilbert, A. An atlas of flaps of the musculoskeletal system. Boca Raton (FL): Taylor and Francis; 2005. p. 184-7.p. 177-83.p. 204-10.p. 218-9.
40. Fraccalvieri M, Bogetti P, Verna G, et al. Distally based fasciocutaneous sural flap for foot reconstruction: a retrospective review of 10 years experience. *Foot Ankle Int.* 2008; 29(2):191–8. [PubMed: 18315975]
41. Uygur F, Evinç R, Noyan N, et al. Should we hesitate to use subcutaneous tunneling for fear of damaging the sural flap pedicle? *Ann Plast Surg.* 2009; 63(1):89–93. [PubMed: 19546681]
42. Parrett BM, Pribaz JJ, Matros E, et al. Risk analysis for the reverse sural fasciocutaneous flap in distal leg reconstruction. *Plast Reconstr Surg.* 2009; 123(5):1499–504. [PubMed: 19407622]
43. Voche P, Merle M, Stussi JD. The lateral supramalleolar flap: experience with 41 flaps. *Ann Plast Surg.* 2005; 54(1):49–54. [PubMed: 15613883]
44. Koul AR, Patil RK, Philip V. Extensor digitorum brevis muscle flap: modified approach preserving extensor retinaculum. *J Trauma.* 2009; 66(3):835–9. [PubMed: 19276762]
45. Chattar-Cora D, Pederson WC. Experience with the extensor digitorum brevis muscle flap for foot and ankle reconstruction. *Ann Plast Surg.* 2006; 57(3):289–94. [PubMed: 16929197]
46. Ortak T, Ozdemir R, Ulusoy MG, et al. Reconstruction of heel defects with a proximally based abductor hallucis muscle flap. *J Foot Ankle Surg.* 2005; 44(4):265–70. [PubMed: 16012432]
47. Levin LS. Principles of definitive soft tissue coverage with flaps. *J Orthop Trauma.* 2008; 22(Suppl 10):S161–6. [PubMed: 19034164]
48. Gould JS, Shi SM. Free vascularized soft tissue flaps for coverage of the foot and ankle. *Clin Orthop Relat Res.* 1995; 314:26–36. [PubMed: 7634644]
49. Keller A. Noninvasive tissue oximetry for flap monitoring: an initial study. *J Re-constr Microsurg.* 2008; 24(8):599–600. [author reply: 601].
50. Keller A. A new diagnostic algorithm for early prediction of vascular compromise in 208 microsurgical flaps using tissue oxygen saturation measurements. *Ann Plast Surg.* 2009; 62(5):538–43. [PubMed: 19387157]
51. van Adrichem LN, Hoegen R, Hovius SE, et al. The effect of cigarette smoking on the survival of free vascularized and pedicled epigastric flaps in the rat. *Plast Reconstr Surg.* 1996; 97(1):86–96. [PubMed: 8532810]
52. Rinker BD, Stewart DH, Pu LL, et al. Role of recombinant tissue plasminogen activator in free flap salvage. *J Reconstr Microsurg.* 2007; 23(2):69–73. [PubMed: 17330201]
53. Whitaker IS, Izadi D, Oliver DW, et al. *Hirudo Medicinalis* and the plastic surgeon. *Br J Plast Surg.* 2004; 57(4):348–53. [PubMed: 15145739]
54. Gideroglu K, Yildirim S, Akan M, et al. Immediate use of medicinal leeches to salvage venous congested reverse pedicled neurocutaneous flaps. *Scand J Plast Reconstr Surg Hand Surg.* 2003; 37(5):277–82. [PubMed: 14649686]
55. Strauch, B.; Yu, H. Atlas of microvascular surgery. 2. New York: Thieme; 2005. p. 234-44.p. 571-89.p. 518-25.
56. Engel H, Gazyakan E, Cheng MH, et al. Customized reconstruction with the free anterolateral thigh perforator flap. *Microsurgery.* 2008; 28(7):489–94. [PubMed: 18683864]
57. Chen HH, Lin MS, Chou EK, et al. Anterolateral thigh perforator flap: varying perforator anatomy. *Ann Plast Surg.* 2009; 63(2):153–5. [PubMed: 19593112]
58. Uluçay GE, Yildirim S, Aydoğdu E, et al. Reconstruction of crush injuries of the foot dorsum: is the latissimus dorsi muscle flap a reliable choice? *J Reconstr Microsurg.* 2006; 22(3):157–66. [PubMed: 16780044]

59. Reath DB, Taylor JW. The segmental rectus abdominis free flap for ankle and foot reconstruction. *Plast Reconstr Surg.* 1991; 88(5):824–8. [discussion: 829–30]. [PubMed: 1833783]
60. Bhattacharya V, Reddy GR. Retrograde perforator-based cross-leg fasciocutaneous flaps for distal leg and foot defects. *Plast Reconstr Surg.* 2006; 117(5):1662–4. [PubMed: 16641757]
61. Nisanci M, Celikoz B, Duman H. Cross-foot island instep flap: a new use of instep skin flap for management of persistent wounds after complex plantar foot reconstruction. *Ann Plast Surg.* 2001; 47(2):127–33. [PubMed: 11506319]
62. Chen H, El-Gammal TA, Wei F, et al. Cross-leg free flaps for difficult cases of leg defects: indications, pitfalls, and long-term results. *J Trauma.* 1997; 43(3):486–91. [PubMed: 9314312]

Fig. 1.
Foot and ankle wound with exposed bone, joint, and tendon requiring flap coverage.

Fig. 2.
Insetting of a latissimus dorsi muscle free microvascular flap to the wound depicted in Fig. 1.

Fig. 3. Sural neurofasciocutaneous pedicled flap. (From Masquelet AC, Gilbert A. An atlas of flaps of the musculoskeletal system. Boca Raton (FL): Taylor and Francis; 2005. p. 187, Fig. H; with permission.)

Fig. 4.
Preoperative markings for distally based sural neurofasciocutaneous flap for lateral open malleolar fracture with soft tissue loss.

Fig. 5.
Inset of distally based sural neurofasciocutaneous flap. The pedicle has been exteriorized.

Fig. 6.
Inset of distally based sural neurofasciocutaneous flap for open distal-third tibia fracture with soft tissue loss.

Fig. 7. Anastomotic arcade of the ankle. 1, superficial peroneal nerve; 2, extensor digitorum longus; 3, perforating branch of peroneal artery; 4, anterior lateral malleolar artery; 5, peroneus longus tendon; 6, lateral tarsal artery; 7, peroneus brevis tendon; 8, dorsal metatarsal arteries; 9, arcuate artery; 10, dorsalis pedis artery; 11, medial tarsal artery; 12, medial branch of deep peroneal artery; 13, lateral branch of deep peroneal nerve; 14, anterior medial malleolar artery; 15, extensor hallucis longus tendon; 16, anterior tibial artery; 17, tibialis anterior tendon; 18, deep peroneal nerve. (*From Masquelet AC, Gilbert A. An atlas of flaps of the musculoskeletal system. Boca Raton (FL): Taylor and Francis; 2005. p. 177. Fig. A; with permission.*)

Fig. 8. Vascular pedicle of the lateral supramalleolar fasciocutaneous flap. 1, ligature of the anterior lateral malleolar artery; 2, anterior tibial artery; 3, deep peroneal nerve; 4, inferior tibiofibular syndesmosis; 5, anastomosis with the lateral tarsal artery. (*From Masquelet AC, Gilbert A. An atlas of flaps of the musculoskeletal system. Boca Raton (FL): Taylor and Francis; 2005. p. 180. Fig. F; with permission.*)

Fig. 9. Vascular pedicle of the extensor digitorum muscle flap. 1, dorsalis pedis artery; 2, lateral tarsal artery. (*From Masquelet AC, Gilbert A. An atlas of flaps of the musculoskeletal system. Boca Raton (FL): Taylor and Francis; 2005. p. 210. Fig. N; with permission.*)

Fig. 10.

Vascular pedicle of the abductor hallucis muscle flap. 1, lateral plantar artery; 2, medial plantar artery, common trunk; 3, medial plantar artery, superficial branch; 4, medial plantar artery, superficial branch; 5, flexor hallucis brevis. (From Masquelet AC, Gilbert A. An atlas of flaps of the musculoskeletal system. Boca Raton (FL): Taylor and Francis; 2005. p. 219 Fig. C; with permission.)

Fig. 11.

Vascular pedicle of the anterolateral thigh flap. 1, descending branch of the lateral circumflex femoral artery; 2, musculocutaneous perforator; 3, rectus femoris muscle. 4, vastus lateralis muscle; 5, muscular branch of femoral nerve; 6, lateral femoral circumflex artery; 7, ascending and transverse branches of lateral femoral circumflex artery. (From Strauch B, Yu H. Atlas of microvascular surgery. 2nd edition. New York: Thieme; 2005. p. 242. Fig. 6–45; with permission.)

Fig. 12.
Open ankle fracture with extensive soft tissue loss.

Fig. 13.
Inset of free anterolateral thigh flap to open ankle fracture with split-thickness skin graft to surrounding avulsion injury.

Fig. 14.

Vascular pedicle of the latissimus dorsi muscle flap. 1, latissimus dorsi muscle; 2, serratus anterior muscle; 3, teres major muscle; 6, axillary artery and vein; 7, subscapular artery and vein; 8, thoracodorsal artery, vein, and nerve; 9, circumflex scapular artery and vein; 10, branch to serratus anterior; 13, pectoralis major muscle. (*From Strauch B, Yu H. Atlas of microvascular surgery. 2nd edition. New York: Thieme; 2005. p. 582. Fig. 11-10; with permission.*)

Fig. 15.

Vascular pedicle of the rectus abdominis muscle flap. 1, posterior layer of the rectus sheath; 2, rectus abdominis; 3, inferior epigastric vessels; 4, anterior layer of rectus sheath; 5, superior epigastric vessels, ligated. (From Masquelet AC, Gilbert A. An atlas of flaps of the musculoskeletal system. Boca Raton (FL): Taylor and Francis; 2005. p. 258. Fig. D; with permission.)