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Review Article

An Overview Algorithm for Perforator Free Flap Coverage of all Zones of the Mangled Upper Extremity

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A truly mangled upper extremity will undoubtedly need composite tissue rearrangement to ensure adequate wound healing; but often also the replacement of missing parts, always with the goal of maximizing functional rehabilitation. Whatever the approach, restoration of the cutaneous envelope surrounding the underlying repaired musculoskeletal system will be mandatory. Vascularized tissues as flaps frequently will be essential to accomplish this goal; however, intrinsic local donor sites not only may not be available due to the injury itself or if chosen would contribute to further injury. Instead, microvascular tissue transfers will play an important role. In this regard, the perforator free flap today has gained prominence as "like can replace like," sensibility is restored, secondary procedures are more simply approached, and donor site morbidity is reduced since no muscle needs to be sacrificed, maximizing function preservation. However, perforator flap donor sites are highly variable, providing another attribute that, on selection, may best meet the requirements for the involved zone of the upper extremity.

A mutilating upper-extremity injury can result in a significant detriment to function and appearance,[1] but a "mangled" upper extremity connotes a vastly greater degree of insult from usually a high-impact trauma. Typically, there will have been crushing and tearing of the limb apart that has resulted in fractures or bone loss, plus nerve, tendon, or vascular disruptions, leaving a potentially devascularized as well as a contaminated or an infected limb (Fig. 1).[2,3] In contrast to the "mangled" lower extremity, Ng et al[3] have stated that "attempted upper limb preservation should be fully exhausted before consideration is given for amputation, which results in significantly decreased function," despite current prosthetic capabilities. This is with the understanding that clinical factors better associated with successful replantation, and perhaps, treatment of the mangled upper extremity would include a sharp/penetrating injury that is not multilevel, more distal level of amputation, absence of an avulsion component or excessive contamination, and a patient with a lesser Injury Severity Score.[4] However, primary amputation in any regard may be a better option in case of hemodynamic instability, as a means to control hemorrhage or prevent the risk of reperfusion syndrome if replantation was chosen yet critical limb ischemia time has been excessive.[5]

If the goal is to salvage the mangled upper extremity, the steps to begin this process will be better outlined by others in this supplemental issue. This is followed by reconstruction of omnipresent composite defects with appropriate tissues, surely leading to a healed wound, and initiating, as early as possible, limb mobilization for restoration of maximal function is essential.[3,6] In addition, sensibility, particularly for the hand, and aesthetic outcomes must always be considered.[2] No matter the encounter, ultimately, cutaneous coverage will be required. Alternatives run the gamut of the reconstructive ladder, starting most simply from primary closure, negative-pressure wound therapy, acellular dermal regeneration templates, skin grafts, to local or regional pedicled flaps.[7] Vascularized tissues, such as flaps, will be the superior alternative to cover exposed joints, denuded bone, implants, or if secondary interventions such as nerve or tendon repairs will be required.[8]

Depending on the magnitude of mangling, resorting to local flaps may be limited due to a paucity of available donor sites or risk of extending additional damage to retained remnants.[2] For these reasons, microvascular tissue transfers, such as free flaps, will play an extraordinary role. Their composition and donor site selection

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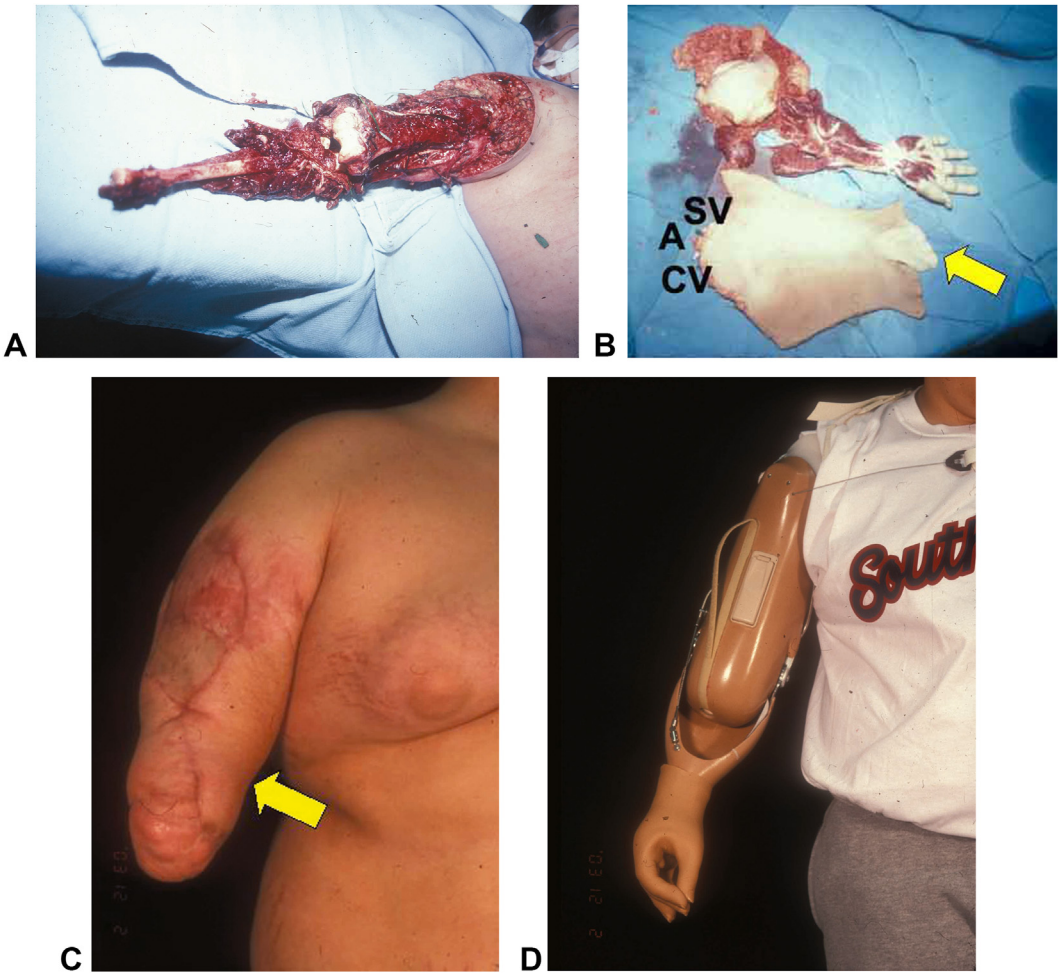


Figure 1. **A** What exactly is a "mangled upper extremity" may be hard to define, but when you see it, you know it. Just so this amputation of the right upper extremity. The humerus and glenohumeral joint remained intact, with extensive remaining local muscle tearing and destruction. The distal fractured radius was avulsed with the degloved forearm and hand, from which the entire ulna and ulnar artery had also been torn away. The proximal radial artery in the amputated part had thrombosed but distally appeared uninjured as was the superficial palmar arch. **B** A forearm fillet seemed prudent as a salvage replant, retaining also the dorsal hand and palm [arrow] planned to cover the humeral stump with more durable glabrous tissues. The radial artery (A) was anastomosed end-to-end to the axillary artery at the shoulder, and a subcutaneous vein (SV) as well as cephalic vein (CV) end-to-end to each of the axillary venae comitantes. **C** This conjoined radial forearm flap completely resurfaced the bare humerus [arrow] to protect the glenohumeral joint. Skin grafts from discarded arm skin were placed on remaining exposed deltoid soft tissues. **D** This young man when last seen was able to pitch a baseball while holding a glove with his fitted prosthesis.

must consider the recipient site requirements so that flap characteristics, such as texture, elasticity, durability, thickness, and always donor site morbidity, must be optimized.[2] Muscle free flaps if chosen strictly for coverage purposes will require nonaesthetic skin grafting and will undergo fibrosis and scarring, often resulting in adhesions to a given wound bed that will make re-elevation for secondary procedures cumbersome.[2,3] Fascial free flaps indeed will be thin, especially valuable for the hand; however, they need to be skin grafted, leading to contracture and similar difficulties if secondary reconstructions were needed.[2] These aforementioned liabilities may be avoided by using fasciocutaneous flaps instead of just restoring the cutaneous envelope, and this is best-exemplified by their genre of perforator free flaps. The latter may, in addition, be sensate while respecting their sine qué non capability for maximizing muscle function preservation.

Zones of the Upper Extremity

Selection of the proper perforator free flap donor site for the given upper limb defect will depend on the latter's dimensions, needed composition, and a pedicle length required to reach an available vascular recipient site. Basic prerequisites will vary according to the anatomical location of the defect. Many years ago, an hypothesis[9] was entertained, primarily based on the available local flap options suggesting that the upper extremity could be divided into three disparate regions much like the traditional zones so commonly described for the lower extremity (Fig. 2).[10] The upper region would correspond to the shoulder and axilla, quite distinct as often regional dorsal thoracic fasciocutaneous flaps from the back would suffice,[11,12] and since not immediately adjacent to the mangled limb remain available in lieu of the rigors of a free flap. The middle region may be trifurcated from cephalad to caudal into three zones, that is, upper arm, elbow and antecubital fossa, and forearm. Local flap options understandably are found least in the most distal region,[13] comprised of the hand/wrist/digits; hence, conventional use of a free flap has often been justifiable.

A better approach if selection of a perforator free flap is indicated perhaps would be to adopt the "expanded zone" concept that Lachica previously introduced for the lower extremity.[14] Instead of zones with rigid anatomical boundaries as was previously

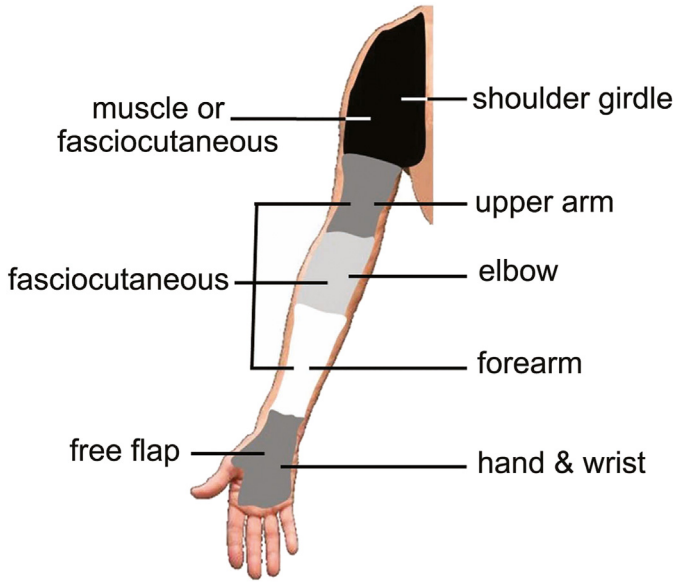


Figure 2. Theoretical zones of the upper extremity based on anatomical location and intrinsic local flap alternatives for potential coverage (modified from Hallock GG[9]).

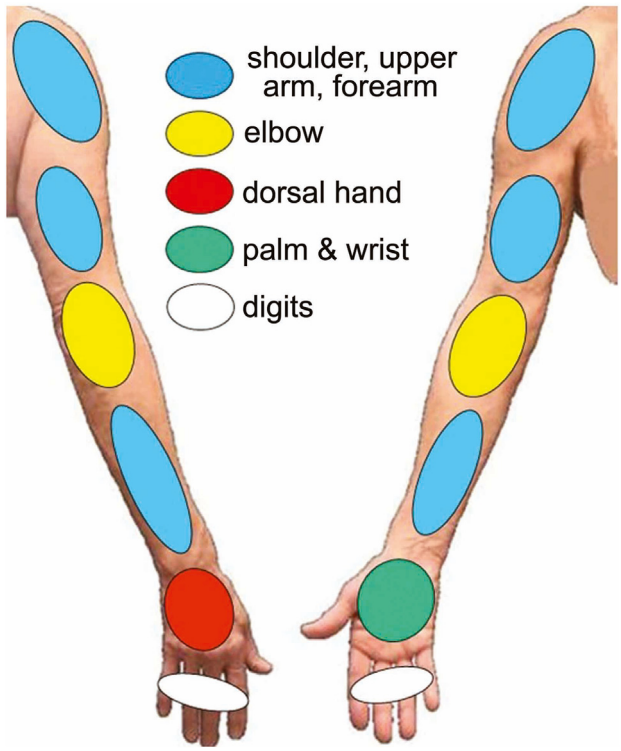


Figure 3. The "expanded zone" concept respects no rigid anatomical boundaries. Flap selection instead should be determined by considering similarities in soft-tissue prerequisites as well as concomitant functional demands for the given upper-extremity location (regions with similar requirements are designated by the same color).

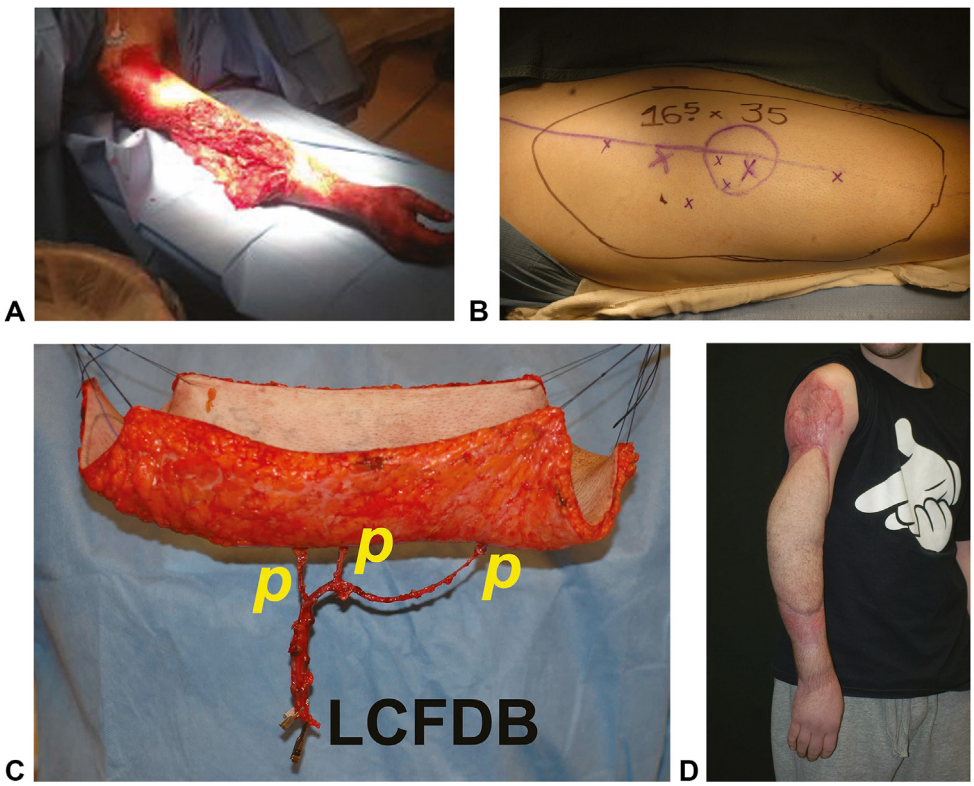


Figure 4. **A** Emergency room view of mangled upper extremity with bone exposure extending from proximal right forearm to arm. **B** Extremely large anterolateral thigh (ALT) flap was chosen to cover all three violated zones. **C** Row of perforators (*p*) intentionally kept in sequence with this ALT free flap to better insure total perfusion. Lateral circumflex femoral descending branch (LCFDB) artery was anastomosed end-to-side to the brachial artery, and veins end-to-end to the brachial venae comitantes. **D** Salvaged upper extremity, followed a year later with multiple tendon transfers to restore wrist and digit extension.

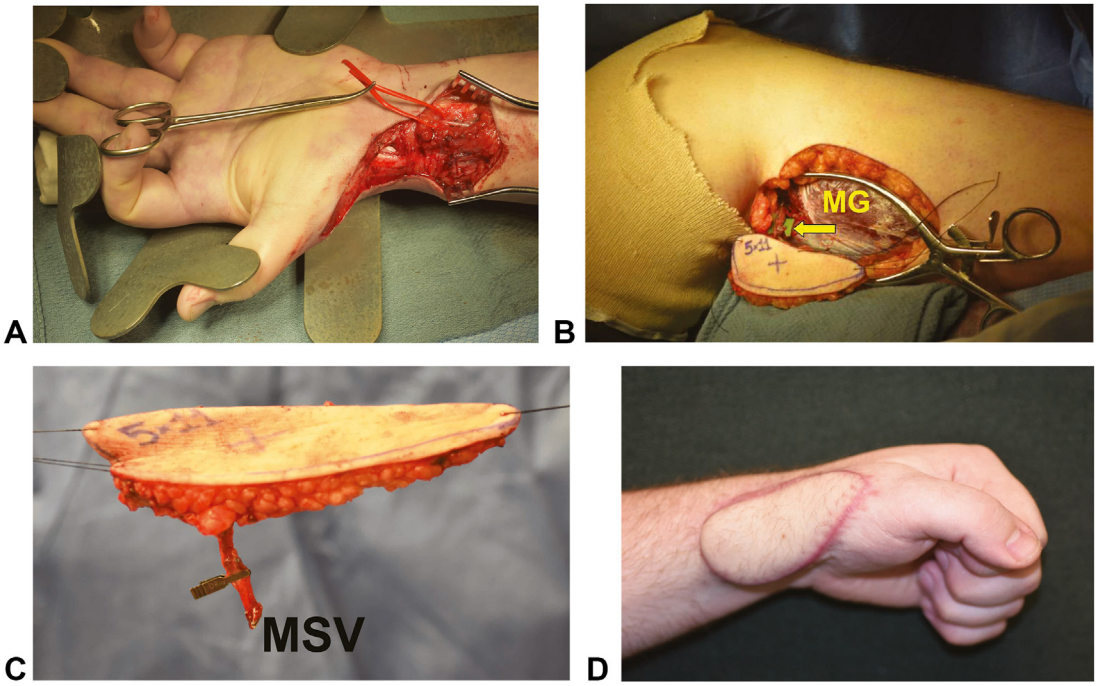


Figure 5. **A** Extensive radial left wrist debridement defect with exposure of multiple flexor tendons. Vessel loop around radial artery that was to be used as arterial recipient site. **B** Relatively thin medial sural artery perforator (MSAP) flap seen in situ overlying medial gastrocnemius (MG) muscle. Arrow points to microgrid under medial sural vascular (MSV) pedicle of the flap. **C** Reasonably thin MSAP free flap based on a solitary perforator. **D** Medial sural artery was anastomosed end-to-side to the chosen radial artery, whereas veins were anastomosed in end-to-end fashion to the larger radial vena comitante and the cephalic vein. MSAP coverage allowed unimpeded digit and wrist flexion.

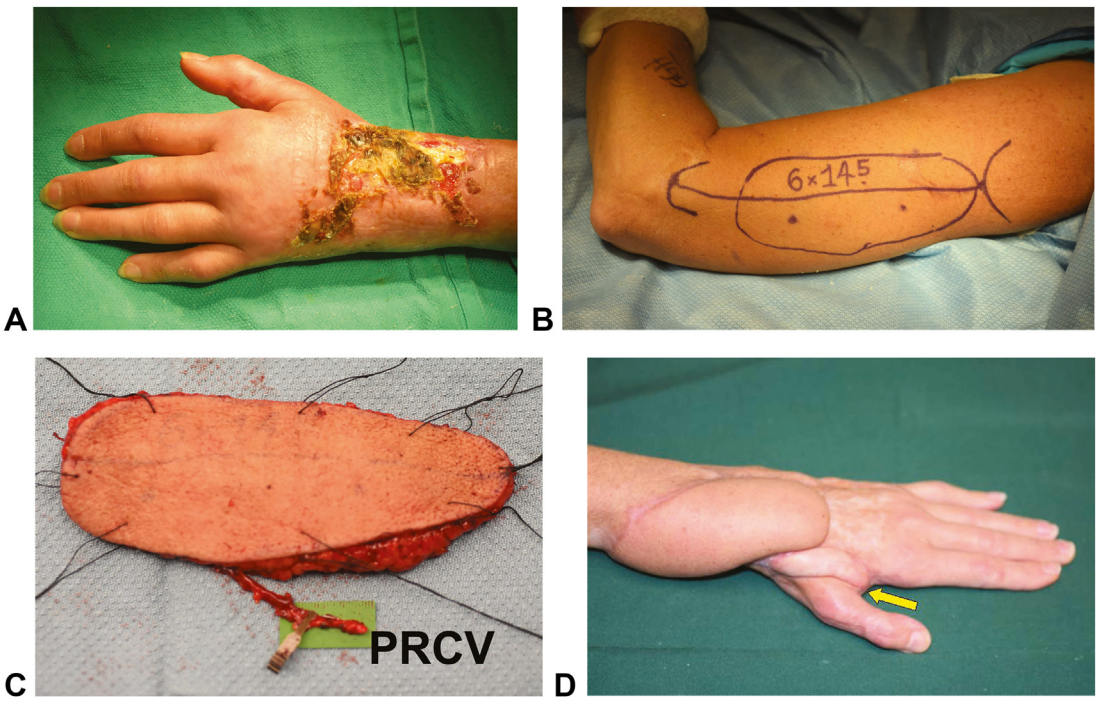
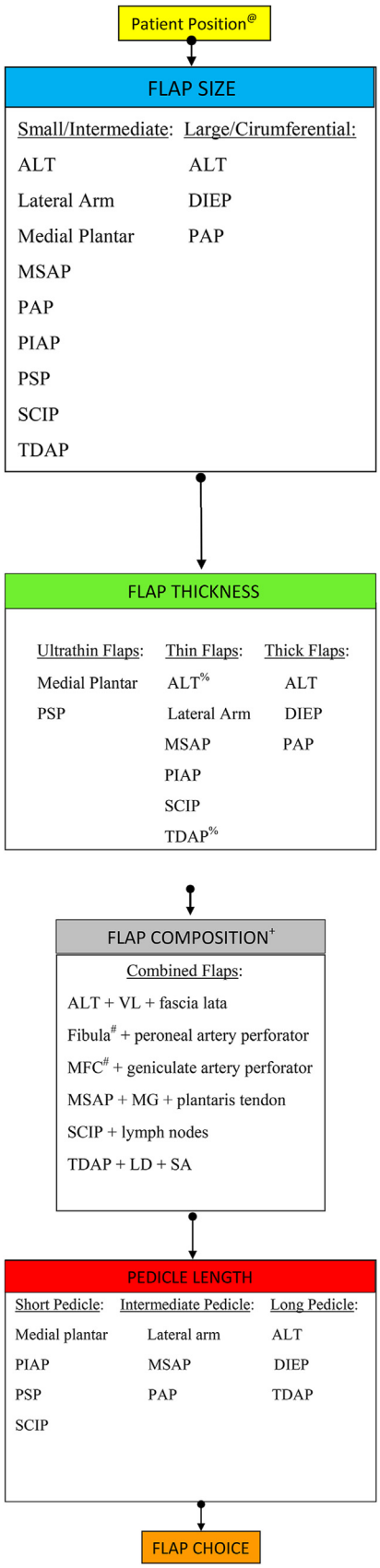


Figure 6. **A** Original nonorthoplastic approach to severe left hand crush and dorsal skin avulsion. Multiple extensor tendons were initially repaired with plate fixation of several metacarpal fractures. Presentation later with wide-spread soft-tissue necrosis requiring debridement, including removal of some tendons and fixation devices. **B** Intermediate-sized free flap was desired but also so that the donor site residue would not be obvious in this young woman. A lateral arm flap was designed about the lateral intermuscular septum drawn between the deltoid insertion and the lateral epicondyle of the humerus, which so chosen would restrict all surgical morbidity to the ipsilateral upper extremity. **C** Lateral arm free flap based on septocutaneous perforators from the posterior radial collateral vessels (PRCV). The flap artery was anastomosed in end-to-side fashion to the radial artery, and a single vein end-to-end to the larger radial vena comitante. **D** Initial skin healing was accomplished, but a year later, the orthopedic service performed a thumb carpal-metacarpal joint arthrodesis to treat an adduction contracture. Coverage of the accrued widened first web space was achieved using the thin, glabrous tissues from a medial plantar artery perforator flap (arrow).

Table 1
Overview of Qualities Algorithm for Perforator Free Flap Selection in the Reconstruction of the Mangled Upper Extremity*



hypothesized,[9] flap choice by region (Fig. 3) would depend instead on (1) similarities of soft-tissue requirements that would include their size, thickness, and durability, (2) functional composition such as to allow pliability over a joint, (3) the technical capabilities of the surgical team, and (4) at least for the plastic surgeon the quality of the ultimate aesthetic appearance.[14] In this context, for example, a reasonably thin free flap would typically suffice for the shoulder girdle, arm, and forearm zones. An even thinner and more pliable flap would be preferable for the elbow or antecubital fossa as well as the dorsum of the hand so as not to limit joint motion. Ultrathin flaps, since they eschew bulkiness, would best restore contour for all the digits, thereby retaining joint mobility. Only glabrous tissues would have the quality needed to meet the requisite durability essential for the palm and digits.

Process of Perforator Free Flap Selection

Each of the numerous perforators throughout the body can sustain its perforasome to potentially be a perforator flap.[15] Thus, a donor site that best matches the characteristics of the given recipient site can be found somewhere as desired. Perhaps that will be from an amputated part that cannot be replanted but instead filleted so that there would be, in a sense, no donor site morbidity (Fig. 1).[4,5,16,17] However, pragmatically, in this search, there will be exceptions to any general rule. Thus, since usually the treatment of a mangled upper extremity will be undertaken with the patient in supine position, a preferable donor site must also be accessible without requiring an inefficient intraoperative position change.

Each potential donor site attribute must be carefully analyzed. Some bulkiness in contour may be more tolerable about the forearm, arm, and shoulder, which justifies the selection of the familiar anterolateral thigh perforator free flap, the “ideal” soft-tissue flap (Fig. 4).[18] Although the anterolateral thigh flap can also be a relatively large flap, the greatest dimensions of all may be possible with a deep inferior epigastric artery perforator free flap from the abdomen.[2,19] However, thinness instead is a quality universally sought throughout the upper extremity and will be proportional to the thickness of the retained subcutaneous tissues. This level can be determined during the surgical harvest of the flap, whether to be superthin (superficial fascia plane), ultrathin (within the superficial fat), or even as a pure skin perforator flap (subdermal plane).[20–23] The pure skin perforator flap is in reality vascularized dermis essentially devoid of subcutaneous fat and otherwise identical to a full thickness skin graft.[20] All these thinner flaps will more likely spare peripheral sensory nerves and deep fascia to prevent muscle herniation as added advantages.[21] Some donor sites are intrinsically thin like the superficial circumflex iliac artery perforator[24] flap from the groin and even the medial sural artery perforator[25] flap from the calf (Fig. 5). Both these have been touted as equivalents for the thin radial forearm flap[26] as that risks loss of the radial artery

ALT, anterolateral thigh; DIEP, deep inferior epigastric artery perforator; LD, latissimus dorsi muscle; MFC, medial femoral condyle; MG, medial gastrocnemius muscle; MSAP, medial sural artery perforator; PAP, profunda artery perforator; PIAP, posterior interosseous artery perforator; PSP, pure skin perforator; SA, serratus anterior muscle; SCIP, superficial circumflex iliac artery perforator; TDAP, thoracodorsal artery perforator; VL, vastus lateralis muscle.
†Most frequently supine.
‡For these flaps, the thickness can be readily adjusted depending on the depth they are harvested.
§All flaps listed here and under the flap size category can also be used as skin only flaps.
‖Important vascularized bone source, but perforator flap in this combination not generally used independently for cutaneous coverage.
* Includes consistently reliable “workhorse” perforator cutaneous flap donor sites[31] (Modeled after Abdelfattah et al[21]).

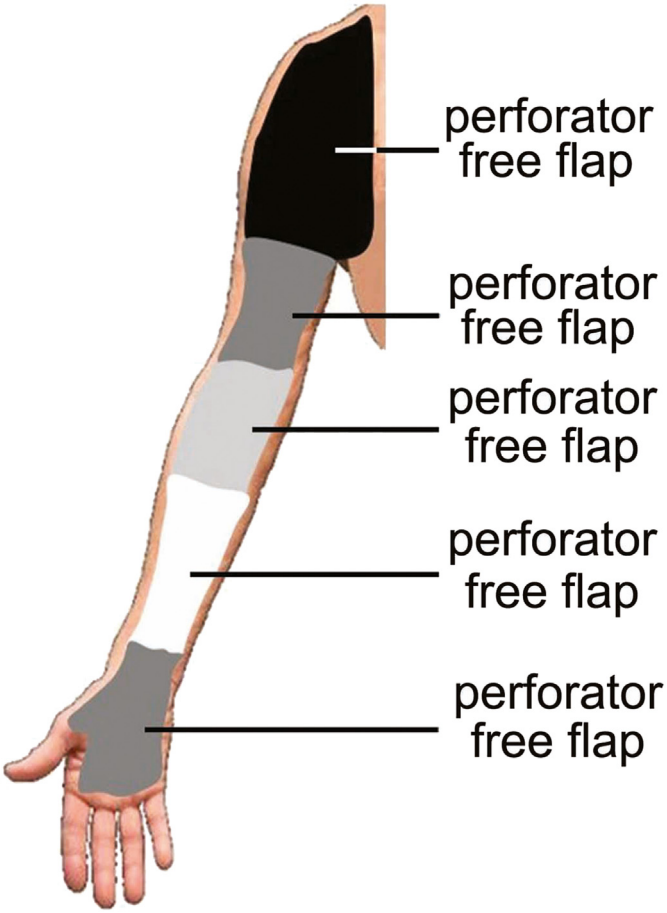


Figure 7. A universal solution if only cutaneous coverage is needed of all upper-extremity zones following a "mangling" injury, if applicable, can be a perforator free flap.

and may leave a poor donor site appearance—both concerns for every hand surgeon so needs no further discussion.[24]

If circumstances allow, workhorse flaps of intermediate size that would restrict all morbidity from surgery to the ipsilateral upper extremity would include the lateral arm[27] (Fig. 6) and posterior interosseous artery perforator flaps,[21,28] both also reasonably thin. The best source for glabrous tissues in quantity would be from the instep area of the foot,[29] where if using the "kiss" flap principle with chimeric flaps in "chain-link" fashion can be combined to resurface an extensive area while still allowing primary donor site closure without a skin graft that often here heals poorly and certainly would be nonaesthetic.[30]

In addition, pedicle length to allow reaching a suitable vascular recipient site without the need for vein grafts will always be an asset. The deep inferior epigastric artery perforator flap may have the longest pedicle,[21] but if too short or small, supermicrosurgery may be required for perforator-to-perforator microanastomoses, indeed an adventure.[28] All these factors are the basis of an overview that in an orderly fashion restates these same characteristics to allow a comparison of the attributes of the more useful "workhorse" flaps and where in the upper extremity they would best be suited (Table 1).

Discussion

Perforator flaps were initially utilized as acceptable free flaps throughout the body with the upper extremity being no exception as Hamdi et al[15] have already proven. The requirements for each will vary depending on the upper-extremity zone and magnitude of injury. The typical "workhorse" donor sites to consider (Table 1) must allow a comparison of specific qualities that would include at least their intrinsic thickness, potential surface area, pedicle length and caliber, and simplicity in harvest and insetting, as well as the need for special technological skills capabilities such as supermicrosurgery. In this regard, perforator free flaps can closely replace the sensibility, texture, pliability, durability, color, and appearance of the reconstructed mangled upper extremity.[2] Not only must physical function and aesthetics be restored, but, as especially true for the hand, detrimental psychological or societal aspects must in concert be addressed by the choice of the best possible surgical approach.[32,33]

Perforator free flaps, of course, are not the only source of tissues that can be used for free flaps in this mangled upper-extremity scenario. Only muscle free flaps can readily obliterate three dimensional voids[2,3] and restore dynamic capabilities as functioning motor units.[2,34] Sometimes, this can be done as a chimeric flap in combination with a perforator flap to capture the advantages of both.[19] Cavadas,[35] during replant salvage, has shown in an urgent situation that use of a muscle free flap can be far more expedient to harvest than the sometimes tedious dissection of a perforator flap perforator. Similarly, for other composite defects, vascularized bone transfers may also be required, sometimes combined with a perforator flap to be a monitor[36] or to augment cutaneous soft tissue to simplify insetting and closure.[37,38] Not all perforators are the same, and therefore, the approach to each must accommodate their innate anatomy, rarely a concern with the common muscle or osseous flaps. After considering all this, ultimately, skin coverage will be required, and the perforator free flap may often solely be the best solution (Fig. 7).

Conclusion

The mangled upper extremity, especially following a crush or avulsion injury to the upper limb, may present as a horrific scenario defying any expectations. Salvage, if chosen, will be challenging to repair and, if necessary, restore all the composite tissues that have been damaged, whether vascular, nerve, or musculoskeletal in origin. Once accomplished, skin coverage will be mandatory, and that typically by some form of vascularized tissues. Local or regional flap donor sites may by this stage of destruction be nonexistent or precarious; hence, cutaneous restoration using perforator free flaps for all zones of the upper extremity can have unparalleled success in permitting wound healing and function rehabilitation and providing a minimally impaired aesthetic result.

Conflicts of Interest

No benefits in any form have been received or will be received related directly to this article.

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