Microvascular Reconstruction of the Upper Extremity

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Abstract

Background: Upper extremity composite tissue defects may result from trauma, tumor resection, infection, or congenital malformations. When reconstructing these defects the ultimate objectives are to provide adequate soft tissue protection of vital structures, and to provide optimal functional and esthetic outcomes. The development of clinical microsurgery has added a large number of treatment options to the trauma surgeon's armamentarium – primarily replantation of amputated tissues and transplantation of vascularized tissues from distant donor sites. Since the early 1970s, considerable refinement in microsurgical tools and techniques together with a better understanding of the anatomy and physiology of microcirculatory tissue perfusion led to the introduction of a variety of thin, pliable and versatile-free flap designs.

Methods: Sources for this manuscript include a comprehensive literature search using the PUBMED and EMBASE databases along with relevant text books, Selected Readings in Plastic Surgery®, and personal experiences of upper extremity reconstruction and microsurgery.

Results: In this manuscript, we describe the primary microsurgical techniques used to reconstruct upper extremity tissue defects and discuss the basis for selecting one technique over another.

Conclusion: Where possible, the best results may be achieved by reattaching the amputated original tissues (microsurgical replantation). In noninfected, uncontaminated traumatic injuries resulting in composite soft tissue defects, *Early* free flap reconstruction of the upper extremities has important advantages over *delayed* (72 h–3 months) or *late* wound closure (3 months–2 years). In recent years, thin, pliable, and versatile fasciocutaneous flaps such as the anterolateral thigh (ALT) and lateral arm (LA) free flaps have been increasingly used with great success to reconstruct the upper extremity. The use of "spare parts" and functional reconstructions using osteomyocutaneous free flaps or toe to thumb transfers complete the armamentarium of the upper limb reconstructive microsurgeon.

Key Words
Upper extremity · Reconstruction · Microvascular reconstruction

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Introduction

> "As the problem is composite, the surgeon must also be .... The surgeon must face the situation and equip himself to handle any and all of the tissues of the limb ..." [1].

Upper extremity composite tissue defects may result from trauma, tumor resection, infection [2], or congenital malformations [3]. When reconstructing these defects, the ultimate objectives are to provide adequate soft tissue protection of vital structures, and to provide optimal functional and esthetic outcomes [4]. These objectives are best achieved in selected trauma cases where the amputated tissues are recovered and can be replanted. In most cases the tissue is damaged beyond repair by trauma or disease (e.g., tumor resection) and the defect must be repaired using local, regional and/or free-tissue transfers from a suitable

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donor area. Microanastamosis of blood vessels and microneurroraphy are required in cases of replantation or free-tissue transfers.

The development of clinical microsurgery has added a large number of treatment options to the trauma surgeon's armamentarium, primarily replantation of amputated tissues, and transplantation of tissues from distant donor sites. In 1960, Jacobson [5] reported 100% patency rates when anastomosing 1.4 mm diameter vessels using microsurgical techniques. In 1962, Malt and McKhann [6] described the first successful arm replantations in two patients. In 1963, a team of Chinese surgeons reported the successful replantation of a patient's hand in which the radial and ulnar arteries were anastomosed using 2.5 mm diameter polyethelene tubes. The same year Kleinert and Kasdan et al. [7] reported salvaging a severely injured upper extremity using a small blood vessel anastomosis technique. While they were unable to replant amputated digits, they did repair damaged vessels and revacularize partially amputated digits. In 1964, Nakayama et al. [8] reported what is likely to be the first clinical series of free-tissue transfers consisting of vacularized intestinal segments. Then in 1967 Komatsu and Tamai [9] performed the first successful digital replantation. In 1973, Daniel and Taylor [10] and O'Brien et al. [11] independently reported reconstruction of the lower extremity using the free-tissue transfer technique. Since the early 1970s, considerable refinement in microsurgical tools and techniques together with a better understanding of the anatomy and physiology of microcirculatory tissue perfusion led to the introduction of a variety of different free-flap designs. Along with these advances came increased free-flap transfer success rates, today reaching levels in excess of 95% [12]. It is generally recognized that the single most important contributing factor for achieving these high success rates is the experience of the operating microsurgeon [13]. In noninfected, uncontaminated traumatic injuries, *Early* free-flap reconstruction of the upper extremities has important advantages over *delayed* (72 h–3 months) or *late* wound closure (3 months–2 years). These include reduced flap failure, decreased postoperative infections, improved bone healing, decreasing duration of hospital stay and a decrease in the total number of operative procedures [14]. A basic principle in reconstruction is "replace like with like". In the case of upper extremity reconstruction, this is best achieved by reattaching the amputated original tissues or through the more recently introduced method of composite tissue allotransplantation of a digit(s), the entire hand and/or forearm from a brain dead donor as is done in solid organ transplantation. In this paper, we describe the primary microsurgical techniques currently being used to reconstruct upper extremity tissue defects and discuss some of the basis for selecting one technique over another.

Decision Making and Planning

When dealing with upper extremity injuries, the reconstructive surgeon is often confronted with the decision to attempt to salvage a badly injured limb or to amputate. In contrast to lower extremity prostheses, those available for upper extremity replacement offer limited restoration of function. Serious associated injuries or disease states such as prolonged ischemia time, and crush, avulsion, contaminated, or multi-level injuries create unfavorable conditions when considering salvage by replantation or revascularization. The multitude of factors and the complex interactions among them make reaching a decision a difficult task, even for the experienced surgeon. The patient's knowledge of the potential risks and benefits of surgery and the possibility of early or later amputation is important [15].

Timing of Reconstruction

Reconstruction may be undertaken early or late. In both cases, the treatment pathways are the same following these steps:

- Adequate debridement
- Skeletal stabilization
- Revascularization
- Soft tissue coverage
- Rehabilitation.

Early *soft tissue* coverage (within 72 h of injury) following complex trauma of the upper and lower extremities is the gold standard. Early is superior to delayed reconstruction with regards to flap failure, postoperative infection, bone healing, duration of hospital stay, and the total number of operative procedures needed [16]. Reconstruction of bone, tendons, and nerves can be performed early or late, depending on the characteristics of the injury and preference and expertise of the treating surgeons. Conditions such as concomitant infection, contaminated injuries, or those with a delayed presentation would favor delayed reconstruction. In the past, delayed, staged reconstruction was the primary method of treatment for severe injuries with multiple structural defects. It is now felt that early reconstruction decreases the number of subsequent procedures, total hospitalization time and cost. In addition, rehabilitation may begin earlier, decreasing the formation of adhesions and improving functional outcomes [17].

Treatment of Complete or Partial Traumatic Amputations

Unsalvageable Injury: Amputation

Case 1: A 23-year-old man sustained a severe crush injury to his nondominant (left) arm, following a traffic accident. The hand was devacularized, with multilevel avulsion injuries to the tendons and nerves and underlying communited fractures. The arm was amputated through the forearm. In this case, the decision was made to amputate based on the multilevel injury, complex bony injury, contamination, and expected very poor functional outcome if replantation was attempted. In such cases a prosthesis can provide better function and a better esthetic appearance than attempts at salvage and reconstruction.

Salvageable Injuries: Replantation/Revascularization

Replantation is the re-attachment of a completely severed body part, whereas *revascularization* is the re-establishment of blood flow in an incompletely amputated part. These procedures have become essential components of emergency hand and upper limb surgery and are amongst the most difficult operations in upper limb surgery. Optimal outcomes require a great deal of clinical experience, appropriate microsurgical equipment and a well-trained multidisciplinary team. The objective of replantation is that the replaced part should provide a better functional outcome than that of a prosthesis.

Case 2: A 30-year-old man presented with a devascularized right thumb caused by a rubber-cutting machine. The only remaining structure between the digit and the hand was a 1 cm wide skin bridge (Figure 1a). This was a significant injury, as 40% of the hand's function depends on a functioning thumb. The patient was taken to theatre where the wounds were debrided and the critical structures were identified. The joint was reconstructed, by reduction of the metacarpal head fracture and placement of two lag screws. Once skeletal stability was achieved the flexor and the extensor tendons were repaired, followed by the digital nerves. Arterial inflow was re-established via the radial artery in the anatomical snuffbox using a vein graft. Venous anastamoses were performed using the transposition of longer subcutaneous veins from the adjacent uninjured area. A split thickness skin graft placed over the ulnar border of the thumb, and thenar eminence provided soft tissue coverage. Long-term

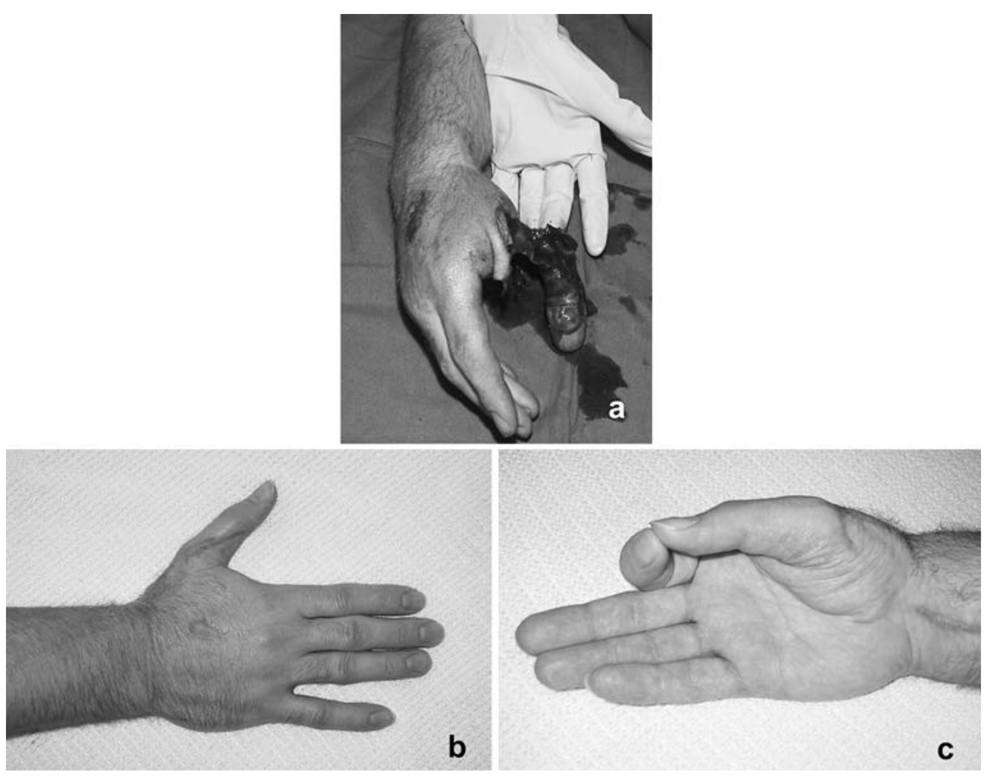

Figure 1. (a)Traumatic sub-total amputation of right thumb. (b) & (c) Post operative result at 3 months.

functional recovery was excellent, following tenolysis of the FPL tendon (Figures 1b, 1c)

As in this case, internal fixation techniques allow early mobilization while maintaining bony stability. Fixation can be accomplished with crossed K-wires [18], a single intramedullary K-wire [19], interosseus wiring [20], intramedullary screws [21] or bone plates and external fixation devices. The type of fixation used is based on considerations of fragment size and stability, early mobilization, patient reliability, and surgeon's preference.

Nerve grafting in replantation surgery is an option where primary neuroraphy is impossible after adequate debridement. Intact donor nerves may be harvested from other amputated and unreplanted parts as long as there is no crush injury suspected, resulting in fascicular damage. Although now over 15 years old, Terzis's excellent review of microneural repair techniques is still a valuable resource [22]. The most common cause of failure of digital replantation is venous insufficiency [23]. Tamai noted that without venous repair, fewer than 20% of replants are successful. The ideal is at least two venous repairs per digit. When the vessel ends are short, or there is tension at the anastomosis, vein grafts are indicated. Buncke et al. [24] review the applications and long-term results of vein grafts in replantation surgery. Digital replants which have become congested are one of the main indications for considering leech therapy [25]. Reports confirm the use of medicinal leeches in salvaging failing replants by relieving venous congestion through vasodilation and vascular decompression [26, 27]. When using leeches, it is important to use prophylactic antibiotics such as ciprofloxacin, due to the relatively high infection risk, normally associated with *Aeromonas Spp.* [28].

Upper Extremity Soft Tissue Defects: Microsurgical Options for Coverage

Faced with large upper extremity composite soft tissue defects, with no viable local or regional options for reconstruction, microsurgical options should be considered. Thirty years ago, free-tissue transfer was performed only in large university centers by a few select pioneers in the field. Today, free flaps are used routinely in many hospital settings with high success rates even in previously perceived "high risk" situations such as elderly patients [29]. Reconstruction of the upper extremity, when there is exposed bone or tendon, particularly in the hand and fingers, requires thin, pliable tissue [30] which allows tendon gliding and a good functional outcome. Bulky flaps, especially near joints, offer poor esthetic and functional results. Here, we describe a range of versatile free flaps which have been successfully used to reconstruct upper limb defects.

Free Fascial Flaps

The free temporoparietal (TP) fascia flap can be used to cover deficits of up to 14.0×12.0 cm in the hand or fingers [31] and is particularly useful in cases where thin, well-vascularized coverage is needed, or to provide a smooth gliding surface allowing unrestricted tendon gliding in the hand [29, 32]. Through scalp incisions, this fascia can be isolated as a vascular island flap (Figure 2a) based on the superficial temporal artery system and the vessel caliber is relatively large (> 1.5 mm) and the anatomy is constant. This flap results in minor donor site morbidity (Figure 2b) and provides good contour on the hand surface (Figure 2c). Other free fascial flaps include those harvested from the forearm [33], lateral arm (LA) [34] and scapular [35] regions. All offer similar versatility when thin, well-vascularized coverage is needed.

Free Fasciocutaneous Flaps

Several versatile free fascicutaneous flaps have been successfully used for reconstructing the upper extremity; these include flaps created from tissues harvested from the anterolateral thigh (ALT), radial forearm, scapular and parascapular regions and the LA.

Free Anterolateral Thigh Flap. The ALT flap was first reported in 1984 [36], and in recent years has become one of the most commonly used flaps in reconstructive microsurgery, especially in head and neck and extremity reconstruction [30]. The ALT flap is eminently suitable for upper extremity reconstruction as it has a large available surface area, long vascular pedicle (from the descending branch of the lateral circumflex femoral artery), can be thinned providing good contours [37, 38], can be neurotized for protective sensibility [39] and the patient can stay supine during harvest [40]. Reliable and satisfactory results for upper limb reconstruction (Figure 3) have been reported in several series worldwide [41–43].

Free Lateral Arm Flap. Lateral arm flaps, based on the posterior radial collateral artery, have been used for soft tissue reconstruction since they were described in 1982 [44]. This option is gaining popularity for covering mid-sized defects of the upper extremity due to its matching recipient skin color, texture, and thickness, in addition to its versatility and reliable

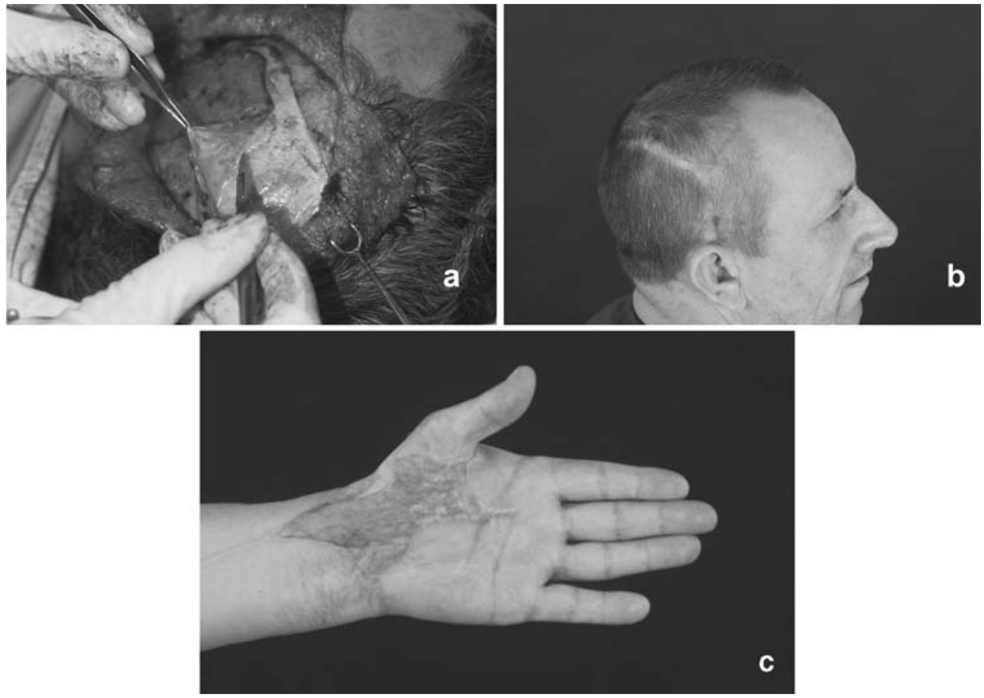

Figure 2. (a)Elevation of free temporal parietal fascia flap through a scalp incision. (b) Donor site at 8 weeks (subsequently covered by hair growth). (c) Healed flap covered with skin graft to the palm following contracture release and median nerve neurolysis.

Figure 3. Antero lateral thigh (ALT) flap used to cover exposed median nerve and brachial vessels on antero-medial aspect of right elbow. The ALT flap was used in preference to split thickness skin graft in order to protect neurovascular structures and prevent contracture limiting elbow extension.

vascular anatomy (Figures 4a–4d). The LA flap may either be harvested as a fasciocutaneous flap, fascial flap [45], or as an osteocutaneous flap incorporating the lateral cortex of the humerus [46, 47]. The posterior cutaneous nerve of the arm may also be incorporated to innervate the flap. The thinness of the LA flap makes it especially useful for reconstructing any of the web spaces. However, more than 10% of these flaps require subsequent thinning procedures when used for hand reconstruction [48].

Free radial Forearm Flap. One of the most commonly used and versatile flaps in contemporary microsurgical reconstruction is the radial forearm flap, which was first described in China in the late 1970s [49]. Its clinical applications were highlighted in a publication by Muhlbauer and Song [50, 51] in 1982. This thin, pliable and relatively large fasciocutaneous flap makes it uniquely suited for covering defects on the upper extremity. The microsurgical anastomoses based on the radial artery and concomitant veins are reliable and regarded as safe and relatively easy to perform. The options to incorporate sensory nerves (lateral antebrachial cutaneous nerve), palmaris longus tendon, and the volar radius [52] make this option particularly useful.

Free Scapular and Parascapular Flaps. First described for upper extremity reconstruction in the early 1980s by Dos Santos [53] and Nassif [54] respectively, the usefulness and versatility of these flaps reside in their unique blood supply – branches of the circumflex scapular artery – which provide the option of complex composite flaps. Free scapular and parascapular flaps may be harvested either as thin, hairless fasciocutaneous flaps, or as osteomyocutaneous flaps to reconstruct complex upper limb defects in which bone is needed. The scapula bone, latissimus dorsi muscle, or serratus anterior muscle plus fascia may all be harvested [55] separately or in a variety of different combinations based on the tissue requirements of the defect.

Figure 4. Lateral arm (LA) flap used to reconstruct a defect in the right hand following resection of high flow ulcerating vascular malformation. (a) Surface marking of the LA flap (left upper arm). (b) Elevation of the lateral arm flap on the posterior radial collateral artery pedicle. (c) Flap inset into the hand. (d) Post operative functional result at 6 months.

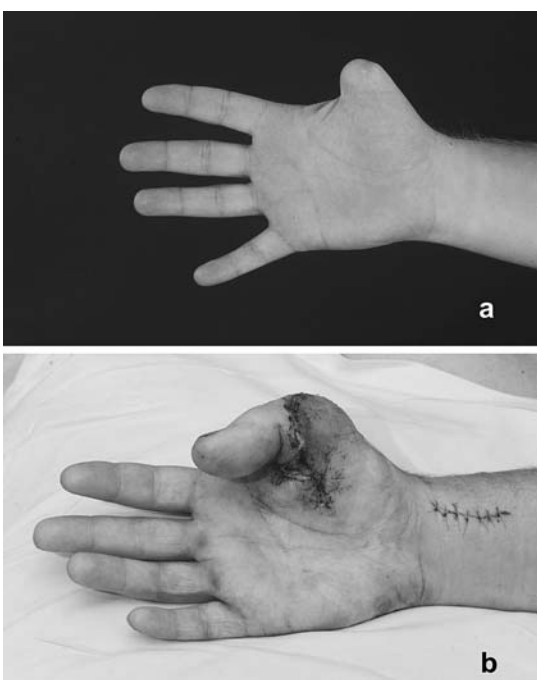

Figure 5. (a) Pre operative view of traumatic amputation of right thumb. (b) Post operative appearance (day 10) following great toe transfer.

Free Muscle Flaps

Muscle flaps are useful when bulk and soft tissue coverage is needed, for example following degloving trauma or osteomyelitis. In 1970, Tamai [56] was the first to report transplantation of vacularized rectus femoris muscle in a dog model. Today, skeletal muscle flap transfer is a common procedure in reconstructive surgery. The most commonly used free muscle flaps are the latissimus dorsi and rectus abdominis muscles, which have reliable, large caliber, long vascular pedicles. These flaps are usually harvested without a skin paddle, and following transfer, their outer surface is covered with a split thickness skin graft. Smaller muscle flaps such as the serratus anterior and gracilis have also been used for the coverage of hand defects [57].

Free Omental Flaps

Free omental flaps have been used to cover nonhealing, poorly vascularized wounds, with the exposure of tendons and joints [58]. Extremity reconstruction using the omentum dates back to 1967, when Goldsmith [59] demonstrated experimentally that the pedicled omentum could be lengthened and placed in the lower extremity. Since then, other authors have described the use of omentum as a pedicled flap for coverage of the upper extremity [60]. In 1968, McLean was the first to use omentum as a free flap [61]. The omentum conforms well to irregular soft tissue or skeletal defects, and the rich lymphatic network is said to have improved resistance to infection [62]. The omentum is not an ideal donor site however. The large resultant abdominal scar, risk of hernia formation, adhesions, small bowel obstruction, splenic injury or intra-abdominal bleeding, mean that it is not widely used.

The Use of "Spare Parts"

The use of "spare parts" from an otherwise unsalvageable limb or digit represents the ultimate form of reconstruction [63]. Undamaged and potentially usable tissues include skin, bone, nerves, tendons, vessels, nail bed, or portions of functional units such as the hand or finger. Every traumatic injury to the upper extremity is different, and the remains of a mutilated upper extremity must be carefully assessed to see if there is any viable tissue available. As early as 1947, Cave and Rowe described using skin from nonfunctional fingers following gunshot injury to cover defects in the hand [64].

"Fillet" flaps are an important part of the armamentarium of surgeons dealing with upper extremity reconstruction. In a polytrauma patient, a nonsalvageable lower limb injury may be used as a donor area for free-tissue transfer to a concomitantly injured upper extremity. The management of such patients requires a close collaboration between the orthopedic and plastic surgery teams.

Functional Reconstruction

Composite tissue transfer offers the ability to reconstruct functional deficits with flaps containing skin, bone, joint, and re-innervated muscle [65]. In addition to providing wound coverage, functional free-tissue transfer can restore stability, sensation, motion and strength.

Microsurgical Reconstruction of Bone Defects

Bone defects measuring < 6 cm in the upper extremity can be effectively managed with bone grafts in the majority of cases. Bone defects > 6 cm and those associated with recurrent nonunions may be candidates for microvascular bone transfer. Various techniques and donor sites have been described to reconstruct bone loss in the upper extremity [66, 67]. Several flaps are available such as vascularized bone including fibula, iliac crest, scapula, LA, radial forearm, and dorsalis pedis. Small defects, such as those in the hand can be managed using LA and radial forearm osteocutaneous flaps. Larger effects of the radius, ulna or humerus usually require larger bone segments such as the fibula. Free-fibula transfer is the most popular due to its accessibility, reliable pedicle and convenient size [68]. Since the initial description of free fibula flaps in 1975 by Taylor et al. [69], several authors have published their successful results with this technique [70–74]. In adults a bone length of up to 24 cm may be harvested, with a vascular pedicle (based on the peroneal artery) of 8 cm, and it may also be used to reconstruct soft tissue defects if it is raised as an osteo-fasiocutaneous flap. The perforators to the skin (branches of the peroneal artery) run around the posterior aspect of the bone, and it is best to include a cuff of muscle along the posterior surface if a skin paddle is to be included. It is important to leave the fibular head at knee level, and 6 cm of distal fibula to avoid problems with the ankle joint.

Free Functional Muscle Transfer

Reconstruction of a destroyed or chronically denervated functional muscle or muscle group in the upper limb is one of the most challenging problems which upper limb surgeons face [75]. Free functional muscle transfer (FFMT) has become an available option in cases where local tendon transfers are unavailable [76, 77]. In instances where there is the need to replace muscle in the forearm or upper arm, it is important that there is a good range of motion of the joints above and below if functional muscle transfer is to be successful. Digital sensation of the affected hand should also be optimized. FFMT involves the transfer of skeletal muscle using microvascular anastomoses in addition to re-innervation by nerve coaptation. Selection of a donor muscle for transplantation must be based on the functional requirements of the patient and the dynamic characteristics of the muscle. Lin et al. [78] suggest the indications for FFMT to be (1) complete loss of upper arm flexors with disruption of the musculo cutaneous nerve (2) complete loss of forearm flexors or extensors with disruption of the innervating nerves and where no local muscle or tendon is available for transfer. Suggested free muscle transfers include gracilis, rectus femoris, and latissimus dorsi, which should be performed as a delayed procedure, as immediate reconstruction with FFMT is associated with high rates of failure [78].

Toe Transfers/Partial Toe Transfers

Microvascular toe transfer represents one of the pinnacles of functional reconstructive surgery, offering the ability to replace part or all of a missing digit with a mobile, sensate toe. Although a complex microsurgical procedure, it remains the benchmark for thumb and digital reconstructions (Figures 5a, 5b). Leung and Frykman describe the technique and functional results of these transfers [79].

Composite Tissue Allotransplantation of the Hand and/or Forearms

If we consider that the aforementioned ultimate objectives for reconstructing upper extremity ''provide adequate soft tissue protection of vital structures, and to provide optimal functional and esthetic outcomes [80]'' it is clear that only replantation of the original tissues can rival the outcomes achievable with composite tissue allotransplantation. Composite tissue allotransplantation (CTA) is now a clinical reality. Between 1998 and 2007, 20 patients underwent 27 hand/forearm/digit transplants (12 monolateral and 5 bilateral hand transplants, 2 bilateral forearm transplants, and 1 thumb transplant) [81–83]. Seven of these are more than 8 years posttransplant and only two graft failures have been reported, one due to noncompliance and the other performed in China, due to unclear etiology. Overall the functional outcomes and patient satisfaction have been reported to be good.

Conclusion

Bunnell's quote introducing this paper adequately sums up the challenge of upper extremity reconstruction. The treatment of complex wounds of the upper extremity with its high density of functional tissue often requires the combination of microsurgical and functional reconstruction. Initial patient assessment and a thorough exploration of the damaged structures are vital. In situations when it is possible, the best results are achieved by reattaching the amputated original tissues (microsurgical *replantation*) or by composite tissue allotransplantation. In complex upper limb defects, where replantation is not possible or indeed necessary, there is a wide range of microsurgical options available to the trauma surgeon. In noninfected, uncontaminated traumatic injuries resulting in composite soft tissue defects, early free-flap reconstruction of the upper extremities has important advantages over delayed wound closure. In recent years, thin, pliable and versatile fasciocutaneous flaps such as the ALT and LA free flaps have been increasingly used with great success to reconstruct skin and soft tissue defects to the upper extremity. The use of ''spare parts'', and functional reconstructions using free muscle flaps and osteomyocutaneous free flaps are also available to deal with composite defects involving loss of muscle compartments and bone defects greater than 6 cm. These more complex procedures have shown more reliable results when carried out as delayed procedures. At the top of the reconstructive ladder, the ability to replace a missing digit with a mobile, sensate toe completes the armamentarium of the experienced upper limb reconstructive microsurgeon. With the development of new and improved immunosuppressive regimens, good medium term results, and increased understanding of composite tissue allotransplantation, upper extremity allotransplants may increase in popularity.

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