Current Concepts in Microsurgical Reconstruction of the Upper Limb

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KEYWORDS

• Upper limb microsurgery • Replantation • Bone gap reconstruction • Soft tissue defect
• Spare part surgery • Toe transfer • Free functioning muscle transfer • Lymphoedema microsurgery

KEY POINTS

- Microsurgery has helped extend the indications for replantation of both digital and crush avulsion amputations.
- Microsurgery has solutions for the coverage of long segment gaps in bone and soft tissue.
- Aesthetics of microsurgical reconstruction is as important as achievement of functional outcomes.
- Toe transfer and free functioning muscle transfer are 2 common surgical procedures that enhance functional outcome of reconstruction during secondary reconstruction.

Video content accompanies this article at http://www.plasticsurgery.theclinics.com.

INTRODUCTION

Microsurgery had a great impact on upper extremity reconstruction by extending the indications of limb salvage in various conditions. With the standardization of the technical aspects of vessel anastomosis of even submillimetric diameter, levels of success are high. The enhanced skill levels and revisiting anatomy have helped us refine our practice to improve outcomes and enhance patient experience. Every aspect of upper limb surgery has been influenced by microsurgery. The current concepts of microsurgical reconstruction of the upper limb are discussed under various aspects of upper limb surgery.

REPLANTATION

The accepted indications of replantation differ from high-volume centers to low-volume centers, with a low threshold for replantation in centers receiving huge volumes.[1] While fingertip replants and replantation of digits distal to flexor digitorum superficialis insertion have been accepted for long, currently, even zone 2 amputations are replanted to get as good results as could be obtained with combined zone 2 flexor injury associated with open fracture of the proximal phalanx[2] (**Fig. 1**). An absolute contraindication for digit replantation that remains is a single-finger or 2 finger amputation with avulsion of flexor and

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Abbreviations

DIEP	deep inferior epigastric artery perforator
FFMT	free functioning muscle transfer
MFC	medial femoral condyle
VLNT	vascularized lymph node transfer

extensor tendons from the musculotendinous level (**Fig. 2**). Replantation of such fingers will affect the function of the other normal fingers. However, a similar amputation of the thumb with the avulsion of flexor pollicis longus and extensors is an absolute indication for replantation (**Box 1**).

A great shift has occurred in the indications of major replants. Over a period, guillotine amputations have become rare, with crush and avulsion amputations being commonplace. In amputations distal to the wrist, functional reconstruction is possible with flaps and toe transfers. In forearm or arm-level amputations, no such reconstructive procedures are possible and prosthesis is the usual option. Although hand transplantation is an alternative, it is currently recommended only for bilateral amputees. Most mangled upper extremities are unilateral injuries, and till the effects of immunosuppression are reduced to very acceptable levels, reconstruction of mangled extremities will be the recommendation.

Technical refinements have made replantation of crush avulsion major amputations much safer. Radical debridement, which involves the excision of muscles in the distally avulsed tendons and the shortening of the bones, is a major step. The former reduces the reperfused muscle load, and the latter, in many instances, facilitates a direct repair of good vessels and nerves and obviates soft tissue cover. Higher rates of primary bone union occur by this method due to the excision of bone devoid of periosteum. Direct repair of structures also reduces ischemia and operation times, reducing complications and cost of care. Up to 10 cm of shortening in either the forearm or the arm segment has not affected function. Once the limb survives, the function can be enhanced by secondary procedures. Quick surgery and approximation of good nerves frequently enable intrinsics to recover, greatly facilitating secondary reconstruction (**Fig. 3**).

FORMULATION OF A SCORING SYSTEM FOR PREDICTING SALVAGE

Has the current microsurgical capability helped develop scoring systems to predict salvage versus amputation of major upper limb injuries? Despite more than half a century of research, a dependable scoring system for salvaging the upper extremity has not come into vogue. The skill levels, attitude, and infrastructure of the surgical team greatly affect decision-making. It is difficult to factor this surgeon element into the overall scoring system. A well-reconstructed upper limb over a period outscores function obtainable through the best available prosthesis.[3]

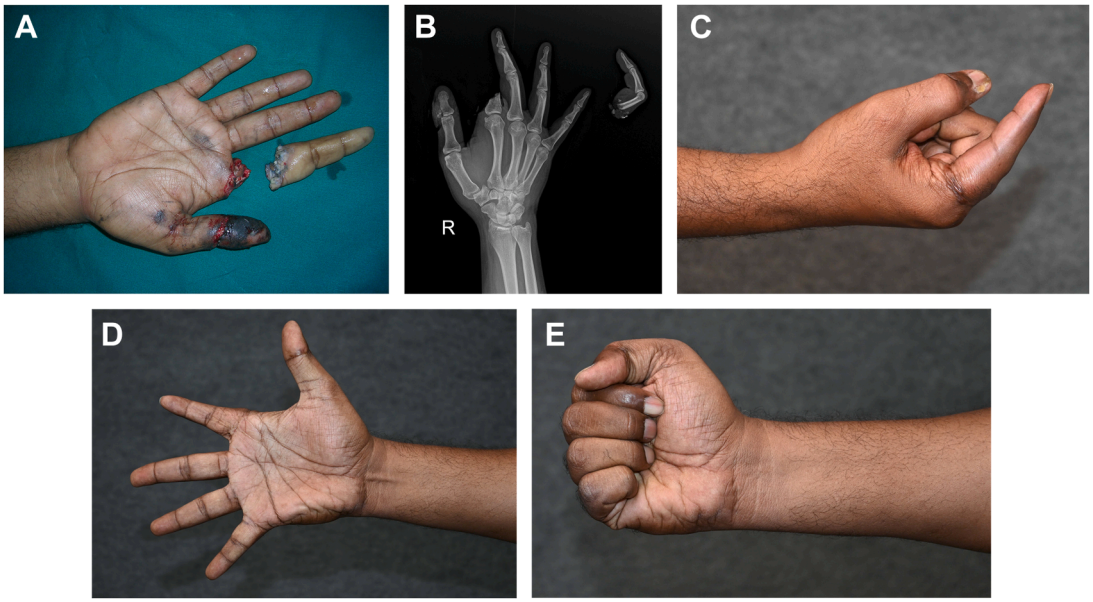

Fig. 1. (*A–E*) Total amputation of right index finger in zone 2. Situation at 7 months after replant, full range of movement after tenolysis of extensors and flexors.

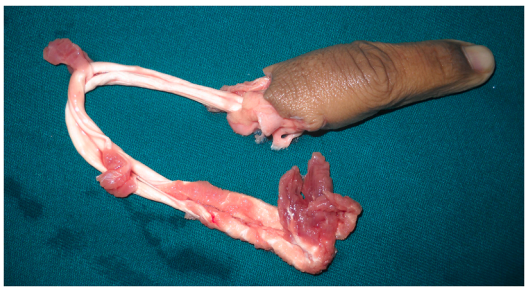

Fig. 2. Single finger avulsion amputations with avulsion of long flexor and extensor at the musculotendinous level remains a contraindication for replantation.

CURRENT CONCEPTS IN RECONSTRUCTING GAPS

Major crush injuries can be associated with long-segment loss of bones, nerves, entire compartments of muscles, and extensive soft tissue loss. When they occur together, they can pose a great challenge. Microsurgery helped us cross this hurdle by providing solutions to cover large gaps with a pair of anastomosis.

RECONSTRUCTION OF SOFT TISSUE DEFECTS

Perforator Flaps

Free flaps revolutionized the soft tissue cover strategy 4 decades ago. Refinements have primarily influenced the practice of soft tissue cover defects of small to very large sizes. Understanding the role of perforators in skin blood supply, delineation of perforasomes[4] coupled with advances in the technology of higher magnification in microscopes, crafting of finer instruments, imaging techniques, and enhanced hand skills have made transferring of flaps that are esthetically and functionally superior.[5]

The perforator-free flap today has become popular because of the concept of "like can replace like," thus reducing donor site problems like insensibility and the need for secondary procedures, thus preserving maximum function.[6]

Box 1
Goal in upper limb reconstruction in major trauma

The goal is to achieve a better functional outcome than that obtained with closing the amputation stump and fitting the best available prosthesis at that level.

This outcome must be obtained within a time frame and at a cost that the patient can afford without putting the patient in any undue morbidity.

Composite Flaps

The other area where a perceivable difference has been made is in the management of composite tissue loss, where composite flaps with a common source of blood supply and their multiple tissue elements are used to cover various components of the defects.[7] Common examples include using the free fibula with a large skin paddle to cover soft tissue and bone defects. The fibula could also be osteotomized to bridge the defect in the long bones of the upper limb[8] (**Fig. 4**) or when covering bone gaps in multiple metacarpal defects.[9] The cover of composite defects needs exquisite planning to reconstruct each defect component optimally. Rarely, flaps have been used in series to cover larger defects.

Free-Style Free Flaps

Free-style free flaps are flaps based on unnamed vessels from donor areas, which are chosen for their best skin color and texture to match the recipient area. The flap can be harvested from any body part if an audible Doppler signal is present without the knowledge of the regional anatomy.[10] Usually, these flaps have a low donor site morbidity as well.

Flow-Through Flaps

The soft tissue cover could also be used as a conduit or a flow-through flap to successfully revascularize an ischemic hand in an acute injury. Here again, the geometry of the vessel gap and the available segment of vessels in the flap must match to make it possible. In the senior author's experience, less than 2% of cases of combined vessel gap and soft tissue defect have been amenable to flow-through flap reconstruction. The commonly used technique is to revascularize the distal part with a vein graft and cover it with a free flap attached end to side to the proximal artery. Flow-through flaps find their greatest application in small defects of the hand and fingers, with flaps raised from adjacent fingers or from the volar aspect of the forearm as venous flaps.[11,12]

Function Versus Esthetics in Free Flaps

Enhancing esthetic outcomes of soft tissue coverage of the hand is currently a priority in reconstruction. Rehim and colleagues[13] found that beyond function, the esthetic satisfaction of the patient depended upon color, contour, texture, hairiness, volume, donor site morbidity, and the nature of the flap and recipient skin interface.

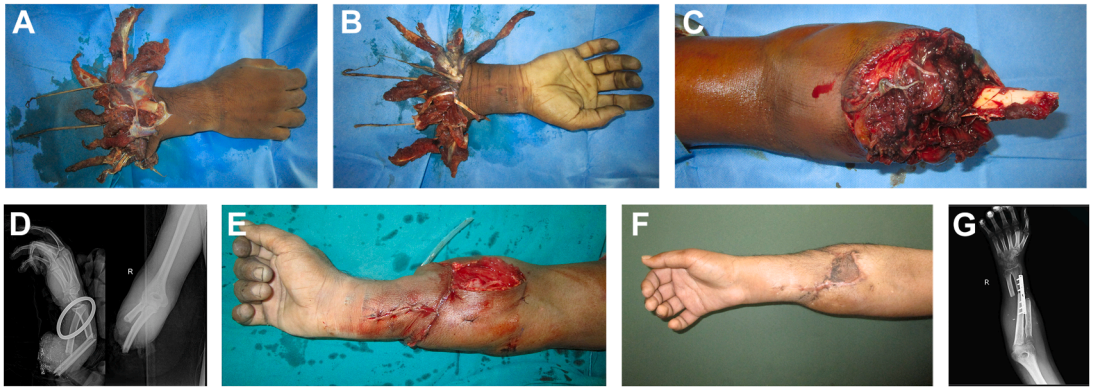

Fig. 3. (*A–G*) Total crush avulsion amputation of the right forearm. Postdebridement picture showing the removal of all the muscles from the distal tendons and the extent of bone shortening. Skeletal fixation by creating a one bone forearm. Replant was successful and ready to undergo a free functional muscle transfer for function.

These aspects need to be considered beyond function. While considering the earlier factors, it is important to realize that a nonfunctional hand is also esthetically unacceptable. The clumsiness of movements increases dissatisfaction. Das De and Sebastin,[14] in that context, stress that function still has to be the priority in the reconstruction of the upper limb. Early flap cover is used to maintain gliding surfaces, and techniques like negative pressure wound therapy are avoided when possible to reduce granulations, fibrosis, and adhesions, which are preferred for a superior functional outcome. The current trend is to concentrate on function and esthetics in microsurgical reconstruction of the upper limb. Debulking of the flap is the most common esthetic surgical procedure done after the flap cover.

CURRENT CONCEPTS OF SENSORY INNERVATION OF FREE FLAPS

In the upper limb, sensory innervation is important in the reconstruction of fingertips and the volar aspect of fingers and palms. In these areas, free

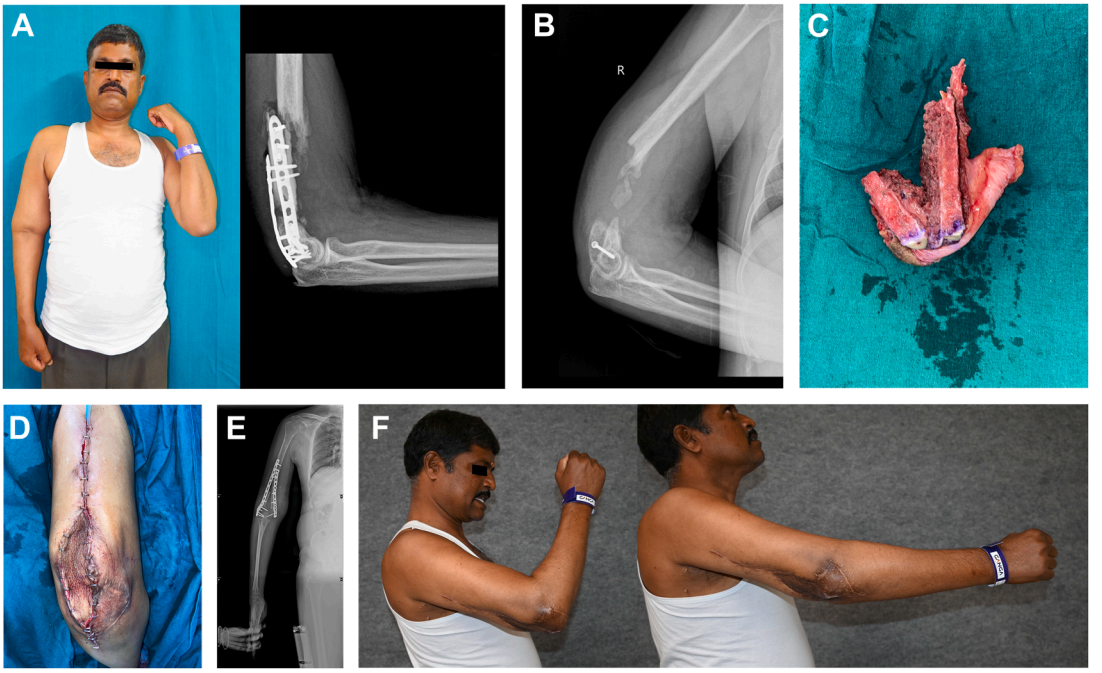

Fig. 4. (*A–F*) Infective gap nonunion of the lower end of humerus with no elbow movement, postdebridement defect, osteotomized free fibula to reconstruct the humerus, postoperative picture showing healing of the nonunion, and restoration of elbow flexion and extension.

flap reconstruction with repair of the nerves supplying the flap is important. For pulp and distal finger defects, toe pulp transfers produce excellent functional and esthetic outcomes.[15] Cutaneous perforator flaps with nerves supplying the flaps are the next best option.[16] For example, palm defects treated with an instep flap continue to be the best color match, which, when innervated by a fascicle of the median nerve through the medial plantar nerve, yields adequate sensation.[17]

Though much research has been done on the sensory recovery of the free flaps in the upper limb, most reconstructions are done for soft tissue cover without nerve approximation. The reason is that the nerves often pass through the flap but do not supply the harvested skin territory. Over a period of years, adequate sensation does recover to functional levels. Smaller and thinner flaps achieve good sensory recovery as assessed by sensory cutaneous pressure testing by Semmes Weinstein Monofilament testing.[18]

After free tissue transfer, small-fiber function recovers with a nerve growth in the direction from the flap margins to the center, likely by way of collateral axonal sprouting from the surrounding nerves in the flap. The myelinated fibers recover slowly.[19]

CURRENT CONCEPTS IN THE RECONSTRUCTION OF BONE GAPS

In posttraumatic long-segment bone loss in the forearm or arm, with the free fibula transfer being commonplace, long bone gaps are no longer an indication for amputation. The critical limit of a 5 cm gap is adhered to in most centers while deciding between a free fibula and a nonvascularized bone graft. Gradually, the acceptable distance is becoming shorter.[20] In the upper limb free fibula finds its best use in the management of infective nonunion (**Fig. 5**). Other donor sites for long bone gaps like iliac crest are not much preferred currently.

A bone with growth center is essential to prevent deformity when reconstructing children, particularly the joint surfaces.[21] Microsurgery with transfer of the upper end of the fibula is the only way to provide a joint surface coupled with growth potential.

Combining vascularized fibular epiphysis with an allograft yields good results and lower fracture rates.[22] Technical refinements are continually made to reduce the donor site morbidity at the knee and the weakness of the peroneal nerve innervated muscles.[23]

Most of the time, microsurgical free fibula transfer is for salvage, while small-sized vascularized bone grafts facilitate early bone union and enhance function. The most commonly used bone flap is the medial femoral condyle (MFC) bone graft, which is used for varied indications like as fixing the nonunion of the scaphoid to that of the tubular bones of the hand and even recalcitrant nonunion of the clavicle.[24,25] Currently, the extensive use of MFC bone graft has shifted the indication to cater to small bone defects with bone union rates up to 95%.[26] With a good understanding of anatomy and surgical skills, MFC vascularized bone graft has less donor site morbidities.[27] In addition, a vascularized periosteum-only flap can be used to wrap the fracture sites to enhance the rates of bone union to up to 99%.[28]

VASCULARIZED JOINT TRANSFERS

Using a combination of tissue from the foot for digital reconstruction can enhance function. Isolating the blood supply of the dorsal skin, split toes, and the interphalangeal joints or a combination of them, has helped us perform good functional reconstructions of fingers. Interphalangeal joints need stability and mobility, and research is being done to improve them through prosthetics and surgical transplants. Proximal interphalangeal joint (PIP) joints of the second toe with a small skin island and extensor tendon repair combined with centralization of lateral bands to improve the extensor lag is now a viable option. An increase in the range of motion of the PIP joint by decreasing the extensor lag to 17.9° makes the outcomes of vascularized joint transfer similar to other existing techniques.[29]

CURRENT CONCEPTS IN CONGENITAL HAND RECONSTRUCTION

Microsurgery finds a place in reconstructing children's hands with loss of digits in symbrachydactyly and constriction ring syndrome.[30,31] In these conditions, the presence of a thumb and a finger makes functional pinch and grasp possible (**Fig. 6**, Videos 1–3). If there is redundant soft tissue beyond the bone in the digits, a nonvascularized free phalangeal transfer is recommended before the age of 1 year.[32] Microsurgery, perhaps, can be the only solution in monodactylous and adactylous hands. In such cases, transferring a single second toe greatly adds to function. Technically, vessel repair in children has not been found to be difficult with the increasing sophistication of microscopes and microinstruments. Though replantations have been done even in newborns, second-toe transfers in children are done around 3 years of age. There may be a paucity of good

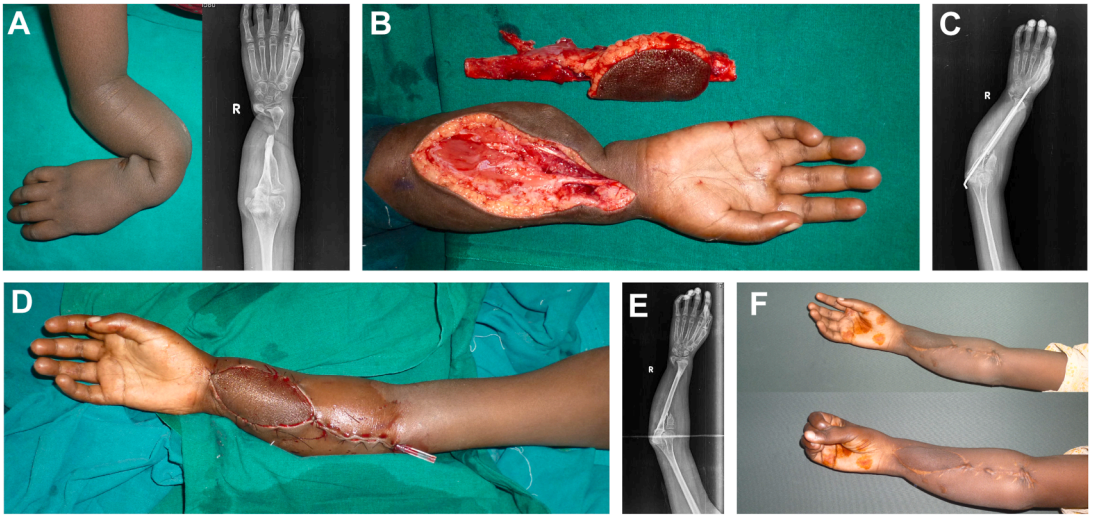

Fig. 5. (*A–F*) Post osteomyelitis nonunion of both bones of the forearm in a 11 year old child. Child had nonvascularized bone graft with failure. Harvested free fibula with a skin island. Fixation with an intramedullary pin creating a one bone forearm. Skin island is essential to facilitate closure, well united bone at 2 years with good functional outcome.

tendons in the forearm. Hence, optimal positioning of the transferred second toe in relation to the existing finger is important to achieve the desired pinch and grasp. Harvest of the second toe in children has almost no long-term morbidity.[33] In our experience, parental acceptance of the procedure and the long-term outcome has been excellent.

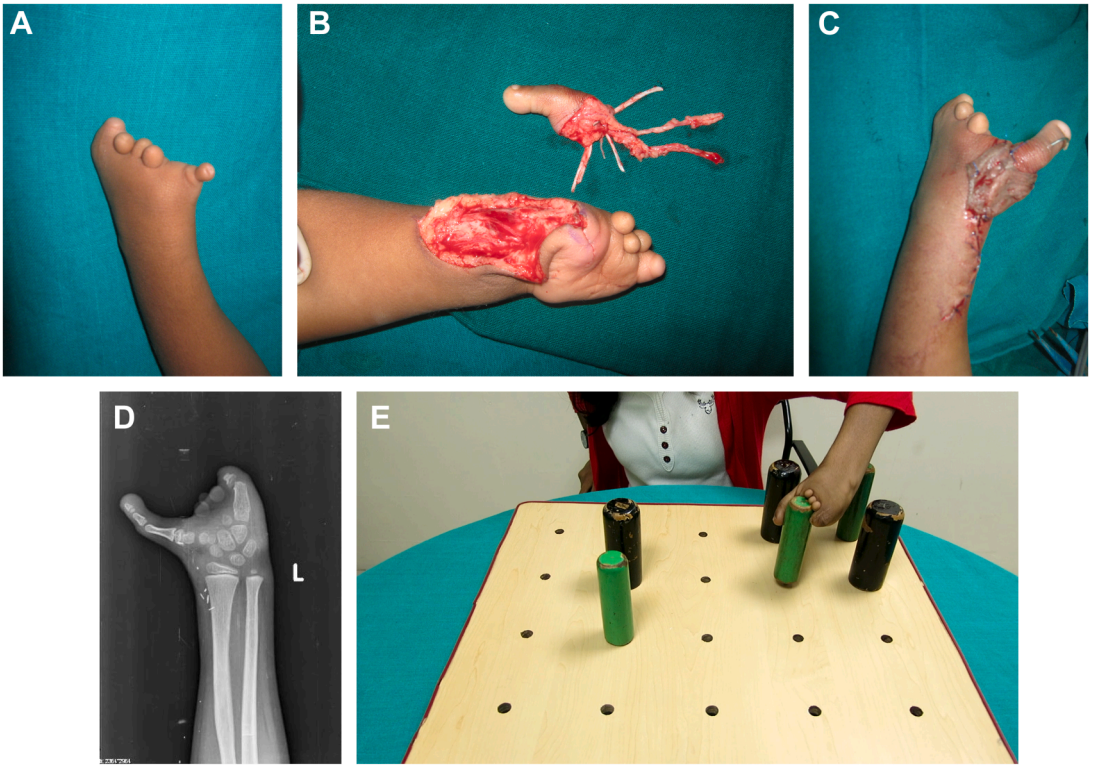

Fig. 6. (*A–E*) Child with constriction ring syndrome with absence of all digits and thumb. Second toe transfer done in the position of the thumb. The transferred toe helps in grip and pinch.

Congenital pseudoarthrosis of the forearm is a rare condition occurring in 2 per 1 million children. Vascularized free fibula transfer has shown to yield 92% to 100% union rates compared to around 70% by nonvascularized bone grafts, so much so that vascularized bone graft has been recommended as the first choice of care and not after complications have set in.[34]

CURRENT CONCEPTS IN THE RECONSTRUCTION OF LYMPHATICS IN THE UPPER LIMB

Upper limb lymphedema is prevalent today due to an increased axillary dissection associated with breast cancer and other malignancies.[35] Although initial treatment in lymphoedema is conservative, various physiologic procedures to restore lymphatic flow are possible if good-quality patterns of lymphatic channels are available on indo cyanine green lymphangiography. Lymphovenous anastomosis can be performed where lymphatic channels are anastomosed to small venules to decongest the overloaded lymphatic system. Multiple lymphovenous anastomoses can be performed to facilitate a bypass for the obstructed lymphatics. The volume reduction achieved by lymphovenous anastomosis is up to 29%.[36] This can only be accomplished in the initial phases of lymphoedema. A 42% reduction in the requirement for compression garments has been observed in patients undergoing lymphovenous anastomosis (LVA).[37]

An alternative pathway for lymphatics through vascularized lymph node transfer (VLNT) is possible in advanced stages.[38] In VLNT, viable lymph nodes from one region are transferred as a free flap to restore the deficient lymph nodes in a specific area. VLNT can be performed either proximally or distally in the limb (**Fig. 7**). The deep inferior epigastric artery perforator (DIEP) flap is typically used to transfer groin lymph nodes to the breast and axillary regions. A mean differential volume reduction of 55.7% can be achieved with VLNT. In addition to reconstructing a breast, the axillary scars are released, and new lymph nodes are introduced, facilitating lymphatic circulation.[39] For patients opting against breast reconstruction, many recommend transferring the VLNT to the distal limb, as excess lymph predominantly accumulates distally. VLNT was also found to reduce the mean number of cellulitis episodes by 2.1 per year. Although there are several donor sites for VLNT, such as the DIEP flap, supraclavicular flap, submental flap, latissimus dorsi flap, and omental flap, extra-abdominal flaps have been seen to have greater volume reductions as compared to intra-abdominal flaps.[40] Every donor region possesses distinct advantages and disadvantages. One must exercise caution with iatrogenic lymphedema that may arise from harvesting these flaps and the potential injury to adjacent tissues during the procedure. Donor-site lymphedema can be mitigated using reverse lymphatic mapping, which employs distinct techniques to identify the lymphatic nodes drained by the flap and the donor site. LVA and VLNT can be combined with liposuction to enhance outcomes.

SECONDARY RECONSTRUCTION

Most severe injuries with bone loss are associated with extensive soft tissue loss. A current trend is to use a combination of nonmicrosurgical and microsurgical options to obtain good functional results. Examples will be the use of toe transfer for thumb amputation at the carpometacarpal joint level, where a preliminary groin flap helps to cover the bare metacarpal during the second toe transfer.[41] Judicious use of pedicled flaps and secondary microsurgical reconstruction yields good results (**Fig. 8**). Awareness of the secondary reconstruction possibilities and low threshold to use free functioning muscle transfers (FFMTs) and toe transfers during secondary reconstruction has extended the indications of limb salvage in severely crushed extremities.

Although toe transfers were initially associated with some reservations due to the donor site morbidity, they have been shown unfounded, as is the fear of cold intolerance in the upper limb and lower limb since a large series of toe transfers have come out from places with cold winters.[42]

There was a tendency to doubt the possible recovery of useful function in proximal nerve injuries. Experience has shown that a good microsurgical repair or reconstruction of the nerve can lead to a useful motor recovery, at least to the first set of proximal muscles. Using these muscles for tendon transfers with arthrodesis of joints can result in useful upper limb function. Even in replantation of forequarter amputation, useful recovery of muscles has been documented.[43]

BRACHIAL PLEXUS INJURIES

An extensive study of nerve anatomy and physiology has revolutionized the management of brachial plexus injuries. Acute brachial plexus injuries require early surgical intervention. The use of nerve reconstruction with nerve grafts or nerve transfers is often dictated by the injury pattern and available expertise. An accurate microsurgical

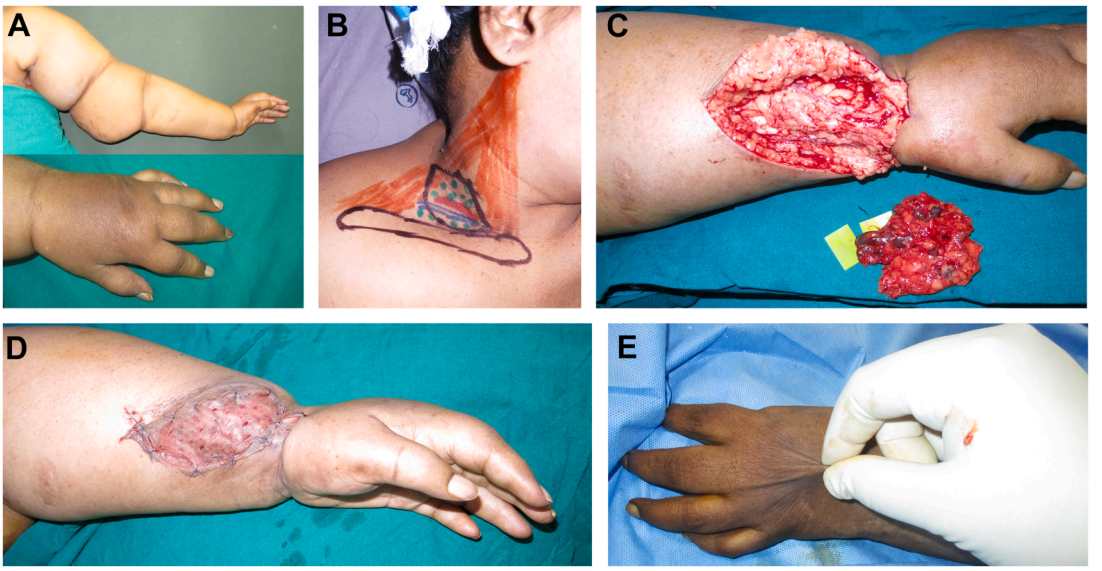

Fig. 7. (*A–E*) Postmastectomy lymphoedema of the upper limb, markings for harvest of supraclavicular lymph nodes, harvested lymph nodes being transferred distally at the wrist level, anastomosed end to side to radial artery, and marked reduction in edema in the postoperative period.

coaptation of the nerves with a good intraoperative nerve identification through nerve stimulation is very useful in achieving good outcomes. FFMT remains an important option for achieving elbow flexion or finger grasp movements in delayed presentations or failed primary nerve repair.[44] The critical sensory zones of the hand comprise the thumb, the radial side of the index finger, and the ulnar side of the little finger. Efforts are made to restore the sensations whenever possible, especially in C8 root injuries where the ulnar side of the thumb tip is numb or in lower brachial plexus injuries where the ulnar side of the little finger needs to be addressed. The donors in such

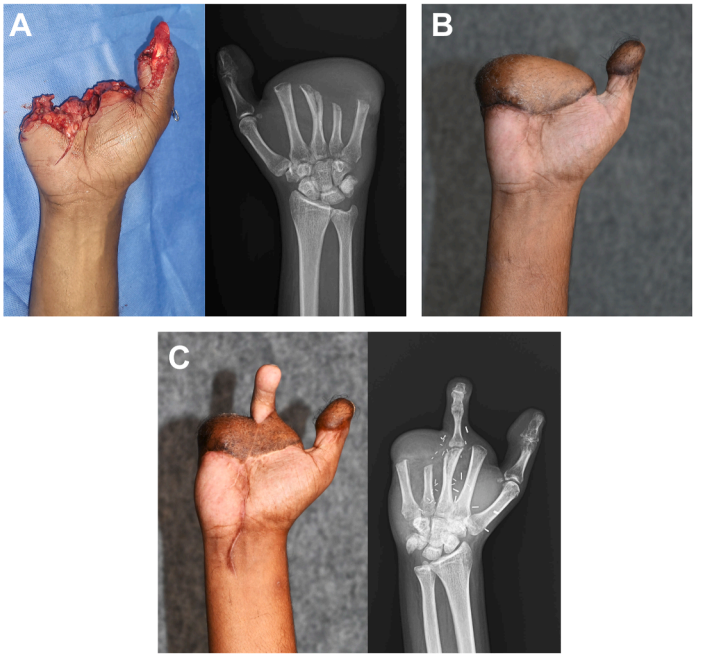

Fig. 8. (*A–C*) Crush amputation of all fingers and pulp of the thumb. Raw area covered with groin and abdominal flap, second toe fixed on the third metacarpal to produce an ulnar post, which provides a good web and facilitates pinch and grasp.

situations could be the palmar cutaneous branch of the median nerve. Distal nerve transfers can offer good motor outcomes in selected patients, like transferring one motor branch of the Flexor carpi ulnaris to the branch of the medial head of the triceps and transferring the branch to pronator quadratus to extensor carpi radialis brevis in C5 to C8 roots injury.[45] Distal radial sensory to median nerve end-to-side transfer is a very effective technique to alleviate pain almost completely, especially in upper plexus injuries[46] (**Fig. 9**).

CURRENT CONCEPTS IN THE USE OF SPARE PARTS

The outcome of a major trauma depends upon the availability of senior decision-making people at the time of arrival of the patient to the hospital. When present during debridement, they can decide to use available nonreplantable tissue to preserve length, obtain soft tissue coverage, or, most importantly, improve the function of remaining less injured digits or hands. The use of "spare parts" needs the ability to think on the spot, knowledge, and skill and also obviate donor site morbidity. The use of spare parts in trauma may range from the use of soft tissue flaps to the entire hand, as in the example of a cross-hand replant in bilateral major crush injuries to the hand.[47]

The spare part concept is now increasingly used in reconstructing congenital hand anomalies where complex anomalies involving both the upper and lower limbs are present.[48,49] If the lower limb is being amputated, the tissues from the lower limb can be used to augment the capacity of the upper limb. This is also used in sarcoma surgery. Distal tissues uninvolved in malignancy can be harvested to augment the salvage of the limb or increase function.[50] A classic example is using the index or other fingers to create the thumb affected by malignancy. In these situations, the tissue to be transferred is kept perfused till the time of transfer, and then further amputation is done. The presence of experienced surgeons at the planning stage is essential for successfully utilizing spare parts.

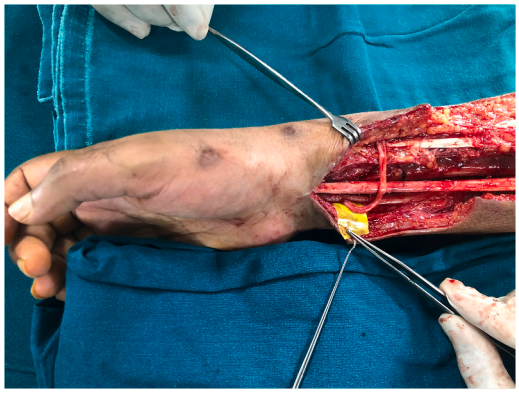

Fig. 9. Distal radial sensory nerve end to side transfer with Median nerve along with tendon transfer surgery in a case of brachial plexus injury for alleviation of intractable neuropathic pain.

SUMMARY

Microsurgery has helped extend indications for salvage in trauma and has refined techniques to obtain excellent outcomes in all aspects of upper limb surgery. Attention to detail during planning and execution is essential to push the boundaries of reconstruction.

CLINICS CARE POINTS

- Microsurgery has impacted every aspect of upper limb reconstruction.
- Fingertip replants have now become accepted as routine in high volume replantation centers with most doing replantation of zone 2-level amputations.
- Finger amputations with avulsion of long flexors and extensors remain a contraindication for replantation.
- Goal of a major replant is to obtain a better functional limb than closure of the amputation stump at that level and fitting the best available prosthesis.
- In spite of large experience of microsurgical salvage of upper extremity following trauma, a scoring system to predict salvage versus amputation still eludes us.
- Free-style free flaps and perforator-based flaps provide good outcomes with low donor site morbidity.
- Esthetics in microsurgical reconstruction has become one of the main yardsticks of measuring outcomes. Flap debulking is the common operation for improving esthesis of reconstruction.
- A nonfunctional hand is esthetically not acceptable.
- Long segment gaps in soft tissues and bone are now amenable for reconstruction.
- Toe transfers can improve pinch and grasp in adactylous and monodactylous hands in children with constriction ring syndrome and symbrachydactyly.
- Various bypass techniques including supermicrosurgery has improved outcomes in both congenital and postsurgical lymphoedema.

- Free functioning muscle transfer, toe transfers, and distal nerve transfers are the important microsurgical procedures during secondary reconstruction of major trauma.

DISCLOSURE

None of the authors of this article have anything relevant to disclose.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at https://doi.org/10.1016/j.cps.2025.09.002.

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