Challenges in Replantation of Complex Amputations

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Abstract

Keywords

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Surgical ingenuity has resulted in continuing microsurgical innovation in replantation. In this article, the authors define complex amputations as those that stretch the boundaries or fall outside traditionally defined indications for replantation. They discuss management of difficult situations involving multiple digit amputations, multiple-level amputations, prolonged ischemia, and multiple trauma. The role of transpositional and ectopic replantation, as well as the requirement for secondary procedures in replantation is also discussed. Although technically challenging, microsurgical management of complex amputations ultimately results in far superior outcomes.

The continuing development of techniques in replantation is facilitated by surgical ingenuity and innovation in dealing with amputations in various forms, levels, and combinations. Perhaps no other organ in the human body in comparison to the hand can be injured in so many ways and by so many mechanisms as to allow an almost infinite variety of approaches to repair of the same basic structures: vessels, nerves, tendons, and skin. Since the first arm replantation in 1962 by Ronald Malt¹ and the first thumb replantation in 1968 by Komatsu and Tamai,² techniques in replantation have progressed exponentially to deal with the various ways in which the hand and upper extremity can be injured and amputated.

Initial attempts to replant every single digit and part were met with varying degrees of success and failure. Hence

criteria for replantation have been described where reasonable survival and anticipated return of function can be expected.³ These include the following: (1) thumb amputations, (2) single-digit amputations (amputations distal to flexor digitorum superficialis (FDS) insertion, distal phalanx amputations, ring avulsion injuries where FDS is intact), (3) multiple digit amputations, and (4) mid-palm amputations.

Other considerations to take into account when deciding whether to attempt replantation include criteria related to the replantation and criteria related to the general condition of the patient. Criteria related to the amputation include mechanism of injury, ischemia, age, and vocation. Guillotine amputations are ideal for replantation, whereas amputations related to crush or avulsion injuries have a generally poor outcome.^{4,5}

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Ischemia time is another consideration when considering whether replantation should be attempted, and is an important predictor of successful replantation.⁶ Recommended ischemic times include 12 hours of warm and 24 hours of cold ischemia for digits, and 6 hours of warm and 12 hours of cold ischemia for major replants.⁵ These guidelines may not apply for pediatric amputations or vocations requiring a high degree of manual dexterity such as musicians, where certainly replantation of almost any amputation digit should be attempted.

The general condition of the patient traditionally has also been a mitigating factor in deciding whether to attempt replantation. Given the short ischemic time window for success of replantation, the adage of “life over limb” would dictate that in the multiply injured patient, resuscitation and life-saving surgery would take priority, hence making replantation a relative contraindication.^{3,4}

Complex amputations are those that challenge or do not follow these general guidelines in selection criteria for amputations. In general, these should only be performed in dedicated microsurgical centers with experience in difficult replantations. The presence of a second microsurgical team³ can reduce surgical time and also fatigue of the primary surgeon. In this article, we review approaches to deal with

these amputations, and also discuss techniques to circumvent relative contraindications for replantation.

Multiple Digit Amputations

Approach and General Considerations

Multiple digit amputations pose a challenge because of increased surgical time required for replantation. However, these have a priority for, and typically constitute an absolute indication for replantation, with the functional result achieved proportional to the number of digits that can be replanted. Different approaches have been described for multidigit replants (►Fig. 1).

A structure-by-structure approach was advocated by Camacho,⁷ where the bones and tendons are stabilized for all the digits before proceeding to the microsurgical part of the procedure. The advantages of this approach are reduced operating time and reduction of incidental injury to repaired adjacent neurovascular structures. Camacho also concluded from their review that survival rate of the replanted digits was higher with the structure-by-structure approach. However, a disadvantage of this approach is prolonged warm ischemia time of all digits and increased blood loss during stabilization of digits. In addition, this approach may not be

Fig. 1 This 18-year-old man sustained a sharp amputation of his three ulnar digits from a machine saw. The volar view demonstrates the level of amputation of the digits (A). The lateral view demonstrates the level of amputation of the long, ring, and little fingers (B). Dorsal view of the three amputated parts (C). At 9-months follow-up, the patient has a good cascade and is able to make a fist (D). At 9-months follow-up, the patient has a functional grip with good strength (E).

feasible where a very large number of digits are amputated, with the corresponding need to keep the individual parts refrigerated and reduce warm ischemia time.

Conversely, a digit-by-digit approach is preferred by several authors. May et al emphasized the importance of restoring pinch and grasp function. Hence, he advocated replantation of the thumb, followed by the middle, ring, index, and little fingers.⁸ Tsai emphasized that reconstruction should focus on the thumb, index, and middle fingers in multiple finger amputations to restore tripod pinch.⁹ A radial to ulnar approach has also been used, with the rationale that the radial-most digits have an increased functional and esthetic importance compared with the ulnar-sided digits.¹⁰⁻¹²

Although both approaches will likely lead to good outcomes in the hands of different surgeons, the digit-by-digit approach becomes increasingly relevant in 9 or 10 digit replantations,¹⁰⁻¹³ which are exceedingly rare due to the different length of individual digits that have to be ampu-

tated by a single mechanism and also due to rarity of all digits being suitable for replantation. The mechanism of injury is often a cutter or press machine,^{12,13} which results in guillotine type amputations to all digits and hence increased survival of replanted digits. A key determinant of success in reported cases has been the prevalence of young, healthy patients involved in these accidents as well as the sharp mechanism of injury with corresponding preservation of amputated digits and structures. Two to four teams of microsurgeons operated simultaneously to reduce ischemia and surgical time.¹⁰⁻¹³ The intermittent use of a pneumatic tourniquet is also very useful in reducing blood loss and requirement for transfusion.¹² In these difficult cases, the functional outcome from multidigit replantation is superior to any other reconstructive modality.

Unfortunately, in most cases, not all the digits can be replanted. In these circumstances, the amputated parts in the best condition should be chosen and replanted in such

Fig. 2 This 22-month-old girl was run-over by a riding lawnmower. She sustained multiple-level amputations of both hands with gross contamination (A). Her right hand was amputated at the radiocarpal joint (B,C,D). Her left hand was amputated obliquely and included her thumb at the level of the carpometacarpal joint and her index and small fingers (E,F,G). The right middle finger was replanted to the thumb position of the left hand. Skin and soft tissue from the neighboring index and middle fingers was included to facilitate wound closure of the left hand (H,I). At 6 weeks, there was osseous union and the patient was beginning to use the replanted digit in her daily life, despite the lack of sensation at this stage (J,K,L).

Fig. 2 (Continued)

positions as to maximize function (►**Fig. 2**). The thumb provides more than 40% of the function of the hand; hence, primary replantation where possible, always takes precedence above all other digits.^{14,15} Where the thumb is lost, transpositional replantation can be used to restore the thumb. Restoration of the thumb and another digit allows basic oppositional pinch,¹⁶ where replantation of a third digit allows restoration of chuck pinch and increased precision handling from restoration of ability for 3-point fixation.¹⁷ Maintenance of the span of the palm through replantation or transposition of digits to the ulnar side is also important to maximize power grasp.¹⁸ Also, restoration of digits of the dominant hand should take priority over the nondominant hand.

Considerations for Transpositional Replantation

Transpositional replantation, or replantation of an amputated digit to another stump, allows maximization of the function of the hand where not all digits can be replanted. Soucacos et al¹⁸ identified five major indications for transpositional digital microsurgery:

1. Multiple digit amputations including the thumb: Where the thumb is not replantable, the best preserved digit is replanted in place of the thumb to maximize hand function.
2. Bilateral thumb amputations: Where the thumb of the dominant hand is irreversibly damaged, the less injured thumb of the nondominant should be transferred to the dominant hand to maximize dexterity.
3. Bilateral, symmetric digital amputations: Digits from the nondominant hand are transposed to the dominant hand to maximize dexterity and function.
4. Multiple amputations with the thumb intact: Replantation of ulnar digits is a priority, to maximize the span and power grasp of the hand.
5. Amputation of all five digits: The priority is to create a functional thumb, followed by restoration of the ulnar digits to maintain the width of the palm and power grasp.

Multiple-Level Amputations

Amputation of hands and digits at multiple levels has traditionally been a contraindication for replantation. However, replantation has been successfully reported in recent years by several authors. Replantation with double level amputation at the palm and forearm was reported by Belsky in 1986,¹⁹ and replantation of segmentally amputated digits was first reported by Liu et al in 1989,²⁰ with survival of three (six segments) out of four (eight segments) fingers. Other authors have reported similar success,^{21,22} with the largest series to date reported by Pei et al,²² with 22 patients. In this series, 20 out of 22 patients had survival of all replanted digits, with partial survival of a thumb in one patient, and loss of two out of four digits in another patient.

Pei et al²² emphasized the importance of multiple microsurgical teams and a digit-by-digit approach to replantation of multiple digits to minimize warm ischemia time. Sequential microvascular anastomoses from distal to proximal levels were also advocated to maintain a bloodless field, and allow

simultaneous perfusion of the entire digit to reduce thrombosis at the anastomotic sites. However, a proximal to distal approach was recommended for multilevel amputations in the wrist and palm to reduce ischemia time in muscles. In cases where the segmental part was less than 1 cm in length, a direct anastomosis between the proximal and distal segments should be performed to reduce number of vascular anastomoses. Vigilant postoperative monitoring and early and continuous rehabilitation was also emphasized as key to ensuring survival and maximal functional recovery in these cases.

Prolonged Ischemia Time

Although guidelines have been recommended in regards to maximal warm and cold ischemic times for replantation, our experience, together with reports in the published literature, suggests that in many cases survival and ultimate functional recovery is not compromised by prolonged ischemia. In many instances, replantation of 8, 9, or 10 digits may mandate prolonged ischemia of the last digits to be reattached. The envelope has been continually stretched,^{8,11–13} with successful replantation of digits after up to 94 hours of cold ischemia.²³ Replantation of the hand has been reported after 54 hours of cold ischemia,²⁴ with satisfactory functional results.

Other factors preventing early replantation include resuscitation in multiple trauma, requirement for other life-saving surgery prior to replantation, or unsuccessful attempted replantation at another institution prior to referral. In a review of 14 patients undergoing 25 replantations after prolonged ischemia of more than 24 hours, Lin et al²⁵ reported a success rate of 64%. Although secondary procedures were required to restore function in several replanted parts, overall functional recovery in the series was satisfactory.

To reduce ischemia time, temporary catheter shunting is a useful modality in major limb replantation.²⁶ Revascularization of the forearm and arm has been reported after 10 hours of warm ischemia²⁷ however, these cases are the exception rather than the rule. In animal models, measures such as ex vivo perfusion with anticoagulated blood²⁸ and drugs such as allopurinol and streptokinase have been useful in prolonging warm ischemia time.²⁹

Ectopic Implantation and Replantation

Temporary ectopic implantation for salvage of an amputated hand was first reported by Godina in 1986.³⁰ He initially conceptualized the use of this technique in severe burns of the forearm where immediate complete debridement of the proximal stump was not possible due to inability to assess the extent of necrosis. Early radical excision in these cases would entail sacrifice of vital structures required for survival and function of the limb. Hence, the intact distal part could be implanted in another part of the body and stored until healing and coverage of the proximal stump, to preserve essential length of the extremity.

This technique was subsequently used by his colleagues and reported in the same article for salvage of a hand with a

proximal segmental crush injury extending for 14 cm over the forearm caused by a corn-picker injury. In this case, the thoracodorsal vessels were used to revascularize the hand temporarily, to allow for dressing changes and coverage of the proximal stump. The hand was ultimately transferred 66 days later using the thoracodorsal pedicle together with saphenous vein grafts to extend the anastomosis proximal to the zone of injury. Ectopic implantation was recommended by the authors for segmental injury of the extremities, with devascularization of the intact distal part, but “extensive, ill-defined and badly contaminated injuries of the proximal segment where radical debridement would lead to loss of important structures.” Mechanisms of injury suggested to be suitable for this technique were agricultural injuries, gunshot wounds, and high-voltage electrical burns, with recommendation for at least 2 months before transfer to allow healing and resolution of inflammation. The authors also emphasized the importance of intensive physiotherapy to the ectopically implanted part to preserve joint motion.

Ectopic implantation was subsequently reported by several other authors for salvage of hands and digits, where the groin and inferior epigastric vessels,³¹ deep inferior epigastric vessels,³² homolateral radial pedicle³³ or opposite forearm³⁴ were variously used as recipient sites. Wang et al³⁵ extended the indications for ectopic implantation, and reported salvage of amputated forearms in two critically ill patients with multiple trauma who were not stable at the initial instance to undergo prolonged replantation surgery. The importance of attaching the tendons of the amputated part to the recipient site to prevent tendon shrinkage and subsequent joint stiffness has been emphasized.^{34,35} Temporary ectopic implantation to the groin was used to salvage impeding vascular failure of a replanted arm due to infection by Cavadas et al.³⁶ In the largest series to date, Bakhach et al³⁷ reported salvage of eight digits using ectopic implantation where the proximal segments were severely damaged and crushed. The dorsal foot and contralateral forearm were used as recipient sites. Based on their experience, they proposed criteria for the recipient site:

1. Recipient vessels: Easy accessibility and similar diameter. Should also be suitable for proximal dissection to lengthen the vascular pedicle.
2. Ectopic site: Stable and away from joints to minimize risk of anastomotic failure and hematoma from movement. Also distant to site of amputation to allow reconstruction of the proximal stump without damage to the ectopic implant.
3. Psychology: Patient should be prepared for temporary change in body image.

Permanent ectopic replantation is also an option in special circumstances. Crossover extremity transfers are useful in cases of bilateral amputations with extensive proximal segmental injury on one side and damage to the distal extremity on the other side.^{38–41} Elective cross hand transfer has been used in a patient with brachial plexus injury leading to a functionless, but intact hand on one side, and loss of all fingers except for the thumb on the other side.⁴²

Fig. 3 This 24-year-old woman had a crush-amputation of her left index, middle and ring fingers. Unfortunately, the index and ring fingers could not be saved and only her middle finger was replanted (A,B). She subsequently developed significant stiffness of the replanted digit with a frozen proximal interphalangeal (PIP) joint (C,D,E). Six months after her date of injury she underwent flexor and extensor tenolysis and PIP joint capsulotomy with much improved range of motion (F,G,H). The replanted finger tolerated this secondary procedure (I); however, her stiffness unfortunately recurred. Although she was able to maintain tip pinch and three chuck grip functions (J,K).

Secondary Procedures in Complex Replantations

Despite best efforts during primary replantation surgery, patients are often left with a poor functional outcome, with tendon adhesions, joint stiffness, fracture malunion, or non-union and scar contractures. Hence, there is often a need for secondary procedures. The incidence of these procedures has been found to be higher in complex replantations involving multiple digits, avulsion, or degloving types of injuries and proximal amputations (►Fig. 3).⁴³

Secondary procedures in the immediate postoperative period include re-exploration of the vascular anastomosis and soft tissue coverage of residual defects using skin grafts or flaps. Following healing of wounds and recovery of the patient, procedures may include tendon transfer and tenolysis to improve range of motion of the replanted digit, or bone graft and arthrodesis to promote bony union. Local tissue rearrangement and secondary flaps may be required for scar contractures. Flexor tenolysis is associated with poorer outcomes in multiple digital injuries, crush or avulsion amputations and those patients requiring proximal interphalangeal joint capsulotomy.⁴⁴ The decision to

proceed with, and extent of secondary procedures performed will ultimately depend on the patient's desire and vocation as well as compliance with rehabilitation and physical therapy. With the many ways available to salvage and replant complex amputations, perhaps the biggest challenge remains postoperative rehabilitation and treatment to optimize patient function.

Replantation in the Setting of Multiple Trauma

Patients with multiple trauma are often critically ill, and may not be suitable to undergo the rigors of a prolonged replantation surgery. With standard trauma resuscitation protocols, life-saving procedures will take precedence over limb salvage. With reports of success in digital and hand replantation after 96 and 54 hours, temporary cold storage of the amputated part is certainly an option prior to early replantation.^{23,24} With more proximal amputations less tolerant of ischemia, temporary ectopic implantation may be the best option if it is deemed that replantation is a viable option.

Temporary intravascular shunts (TIVSs) are another option where physiologic derangement of the patient mandates

damage control prior to definite replantation. The indications for TIVS⁴⁵ include the following: multiple severe vascular injuries, ischemia for 6 or more hours after an injury, arterial injuries in more than one extremity and replantation of avulsed limbs. Much of the recent experience with TIVS has been in management of wartime injuries where TIVSs are placed for 2 to 6 hours to allow evacuation of the patient from the frontline to a higher echelon of care.^{46–48} Temporary intravascular shunts have also been used in mangled extremities while debridement is performed in perfused limbs to allow better assessment of tissue viability, and to permit shorter surgical time in damage control prior to definitive limb salvage surgery.⁴⁹ Temporary intravascular shunts have been used successfully in shunting of the brachial, radial, and ulnar arteries.⁵⁰

Shunts are classified into straight in-line or looped shunts, and are secured in place with vessel loops or silk ties. Systemic anticoagulation is not required,⁵⁰ as many multiple trauma patients are coagulopathic anyway. In a large series of TIVS use over a decade,⁵⁰ it was reported that arterial shunts remained patent at least 71 hours and venous shunts at least 35 hours. Certainly, when used, TIVSs should be removed as soon as possible due to risks of thrombosis and infection.

Conclusion

Advances in microsurgical equipment coupled with surgical ingenuity have allowed replantation of increasingly complex amputations. Often the key to restoring function does not rely on exact anatomical restoration of amputated digits, but might lie in transposing a better preserved part to a more suitable proximal stump. Management of these patients is often complex, and requires a series of secondary surgeries to optimize function. The requirement for secondary procedures and rehabilitation is amplified in complex amputations, and requires patient compliance and understanding of the protracted course of treatment. However, functional restoration of the upper extremity with microsurgery has been, and continues to be, superior to all other forms of surgical or prosthetic modalities of treatment.

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