MINI-SYMPOSIUM: HAND TRAUMA

(v) Upper limb amputations: Where, when and how to replant

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Summary
This review looks at the history of replantation in the upper limb, and how both survival of the amputated part and functional outcomes have improved with increasing microsurgical experience. We discuss the relevant considerations when part of an upper limb is amputated, and the indications and contraindications to microsurgical replantation. The practicalities of managing this injury that threatens limb, and sometimes life, are highlighted, together with key points from our suggested operative management plan. Finally, we review the current literature with regard to prognosis and functional outcomes that can be achieved when replanting an amputated part of an upper limb.

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Introduction

In 1964, Malt and McKhann performed the first microsurgical reattachment of an amputated upper limb,1 thus answering the question of whether limb replantation was possible. Subsequently, technological advances and surgical experience with such injuries have allowed us to question not whether we can replant an amputated part, but whether we should replant an amputated part.

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and the necessary technical skills and resources, excellent outcomes can be achieved.

**General considerations in amputation of the upper limb**

The condition of the amputated part as it arrives at the medical institution for consideration of replantation is important, but is not the sole determinant of whether replantation should be undertaken. Factors that must be weighed to decide whether the part should be replanted include the patient’s overall clinical status (including suitability for long-term rehabilitation), the condition of the amputated part, the complexity of the microsurgery required and the significance of the amputated part to the patient’s upper limb function and activity. These considerations are applicable to all amputations but are of varying importance depending on the level of amputation.

**Considerations related to level of amputation**

- The more proximal the amputation, the more significant the overall health risk of replantation due to the pernicious systemic effects of reperfusion of skeletal muscle.
- The more proximal the amputation the more prolonged and complex the rehabilitation because of the requirements of nerve regeneration. For some individuals protracted physiotherapy may be inappropriate.
- The more distal the amputation, the less uniquely valuable to the patient the amputated part is likely to be and the more technically difficult the microsurgical repair, although rehabilitation may be less complex and shorter in duration.

The financial implications of upper limb replantation are also significant. A recent study from the United States put the cost of single digit replantation at $20,330. This, combined with the magnitude of subsequent Disability Benefit payments, emphasises the very high monetary cost that follows a decision to replant. Surgeons should also bear this in mind when making such judgements, especially in a state-funded healthcare environment. To relieve the onus on the individual, many units adopt policies and guidelines about the worth of replantation in each circumstance.

**Spectrum of injury**

There are several ways of categorising upper limb amputations:

- Clean cut versus crush or avulsion.
- Clean versus dirty.
- Tidy versus untidy.
- Simple versus segmental.
- Distal versus proximal.

A clean cut or guillotine-type amputation results in less trauma to adjacent tissues of the affected limb, and is characterised by structures that have been sharply divided and are suitable for precise primary repair without an extensive zone of injury (Fig. 1). Crush or avulsion injuries are associated with more widespread trauma to the affected limb: traction forces cause structures to tear at their weakest point or heavy loads crush tissues (Fig. 2). Avulsion injuries cause a shearing force along vessels,
associated with a “red line” or “ribbon” appearance caused by separation of the intima from the media. It has been seen that vessel anastomosis within these damaged sections leads to higher complication rates secondary to vessel thrombosis, making vein grafting after resection of the damaged section appropriate.

Figure 2  (a, b) These images highlight the significant trauma associated with avulsion injuries. This boy’s hand and wrist were amputated after a twisting avulsion injury at the level of the mid-forearm. (c) The long-term outcome after replantation. Surgery involved complex skin cover by microsurgical free tissue transfer. Original replantation involved considerable skeletal shortening despite which several procedures were also needed to graft nerves and vessels. This boy had poor hand function even after intensive rehabilitation, and poor growth of the replanted part.
Classification systems

Several classification systems have been developed to guide the clinician in making the decision to replant. These systems can be useful for describing an injury and for predicting post-operative outcomes, so that similar injuries can be compared.

An example is seen in ring avulsion injury, where the integument to the finger (usually the fourth finger) is torn from the skeleton when an ornamental ring is caught in a belt during the application of large forces, for instance when a ring catches on a metal fixture as the wearer jumps from the back of a trailer. Urbaniak described a system for placing ring avulsion injuries into three categories. Kay et al. modified this work in 1989 after reviewing a large series of such injuries, resulting in the classification system seen below. Previously complete amputation was considered a contraindication to replantation, but this system emphasised that in fact complete ring avulsion amputation may be more favourable for replantation.

Kay et al. Classification of ring avulsion injuries

1 Circulation adequate. Treat with standard bone and soft tissue techniques
2a Inadequate arterial supply, without skeletal injury. Suitable for vascular repair alone
2b Inadequate venous supply, without skeletal injury. Suitable for vascular repair alone
3 Inadequate circulation with associated skeletal injury. Suitable for vascular repair following bone or joint repair. Because the part is not completely amputated the option of skeletal shortening is restricted
4 Complete injuries. Suitable for replantation with the advantage that the skeleton may easily be shortened, often avoiding the need for vascular or nerve grafts. In the ring finger such shortening can be considerable, limited only by the need to avoid a length less than the adjacent little finger

A classification system has also been developed for traction avulsion amputations, based on the level of avulsion with regard to musculotendinous units. This consideration determines function after repair in the upper limb, and allows prognosis after replantation to be predicted and therefore management strategy formulated.

Chuang Classification for traction avulsion amputations: Increasing grades are associated with poorer outcomes

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
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<tbody>
<tr>
<td>I</td>
<td>Avulsion close to musculotendinous aponeurosis with muscle remaining intact &amp; functional</td>
</tr>
<tr>
<td>II</td>
<td>Avulsion through the muscle belly but distal to the neuromuscular junction with innervated proximal muscle</td>
</tr>
<tr>
<td>III</td>
<td>Avulsions within the muscles but at or proximal to neuromuscular junction, with the entire muscle being denervated and/or destroyed</td>
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<tr>
<td>IV</td>
<td>Avulsion through the joint (elbow or shoulder disarticulation)</td>
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The decision to replant is clearly not always straightforward and other attempts have been made to develop injury scoring systems to identify the patients who would benefit most from replantation. Durham et al. evaluated the most popular scoring systems (MESI and MESS) but found limitations both in the practical application and relating to poor sensitivity and specificity. Neither system was able to predict functional outcome, nor were they able to predict which patients would do better with a salvage procedure over a primary amputation. These scoring systems therefore do not contribute greatly to the decision as to whether to replant or not, which remains clinically based and largely determined by experience, individualised to the particular patient and his or her needs. However, some general indications can be summarised.

Indications for replantation

The indications for replantation are based on the probability of survival of the replanted part, the safety of the procedure for the patient, the likely functional outcome, the value of the part to the patient compared with the resources consumed to replant it (i.e., the cost) and the patient’s wishes.

Many surgeons now believe that the outcome does not usually justify a single digit replantation and in general single digits should not be replanted, with certain exceptions:

1. The patient is a child.
2. The digit is a thumb.
3. The mechanism is a ring avulsion injury (see previous discussion).
4. It is at a level distal to the flexor digitorum superficialis (FDS) tendon insertion (work by Urbaniak has shown that results of replants proximal to this level are less functionally acceptable—discussed further below).
5. The patient has special needs such as in the case of a professional musician (who surprisingly rarely injure their hands).
6. The patient already has a compromised hand (through previous trauma, congenital anomaly or other condition affecting hand function).

By contrast, and in keeping with the final indication above, where the injury involves multiple digit amputations (so creating a severely compromised hand), or in the case of a more proximal amputation, replantation should in general be undertaken unless:

1. The patient has co-morbidities precluding major microsurgery and rehabilitation.
2. The amputated part has been incorrectly preserved in ice and consequently suffered frostbite.
3. The amputated part has segmental injuries or is severely mangled (Fig. 3).
4. There is a prolonged ischaemia time and concern regarding reperfusion injury and systemic injury.
5. The amputated part cannot be located or there is confusion about whether the part belongs to the patient, for instance in the rare situation where there are multiple victims with amputations.
Initial assessment and management

A patient with an upper limb amputation must be systematically assessed for co-existing injuries and resuscitated as necessary. Haemorrhage from the stump should be stopped and exposed tissue preserved by applying a non-adherent pressure dressing and elevating the limb. A tourniquet is not necessary and can be dangerous. All limb bleeding can be controlled by anatomically precise, focused local pressure constantly applied until definitive control is secured in the operating room.

Preserving the amputated part in a cool, moist environment whilst protecting it from frostbite extends the time before irreversible damage is sustained secondary to anoxia, and is a major factor in replant survival. This can be achieved by wrapping the part in saline-soaked gauze, placing it within a sterile bag, and refrigerating it at 4°C. Alternatively, the same sterile bag can be chilled by placing it on (but not in) ice.

When the patient presents primarily to a medical unit that does not have the facilities for replantation, the patient must be urgently transferred to a microsurgical centre, as the decision to replant or not should be made in a unit where there is experience of replantation and all the management options are available. Uninformed decisions deny the patient the benefits of reconstruction and represent a failure in the duty of the care we owe our patients.

There is no defined ischaemia time that precludes replantation. This is determined by whether the part has been appropriately preserved and whether the part contains a significant mass of muscle. Digital amputations have no significant muscle content and have been shown to be viable after more than 24 h of refrigeration. For amputated parts with significant muscle content it has been recommended that delay to revascularisation should not exceed 6 h. This is to prevent rhabdomyolysis, myonecrosis and subsequent life threatening reperfusion injury as well as the pernicious consequence of fibrosis and scarring.

Operative management

The amputated part should be inspected under the operating microscope for vessels suitable for anastomosis and all other relevant structures should be identified and inspected. This can be performed while the patient is being

Figure 3 (a, b) An example of an upper limb amputation that was not suitable for replantation. The arm stump shows massive soft tissue destruction with separation of radius and ulna by rupture of the interosseous membrane, after a traction avulsion amputation through the proximal forearm. The amputated part shows the degloved skin and head of the radius that has been disarticulated from the elbow joint. The energy dissipated was considerable and the widespread avulsion makes replantation very difficult and the functional prognosis very poor.
resuscitated, transferred to theatre or is undergoing anaesthesia. It is sometimes useful to tag small vessels with marker sutures to ease identification later, after bleeding has obscured anatomical landmarks.

As with any trauma case, debridement of dead tissue and thorough washout of the stump and amputated part is important, converting a dirty or untidy wound into a clean, tidy one. Full advantage should be taken of any opportunity to shorten the skeleton if this aids or is enforced by debridement, or allows tension-free repair of nerves or vessels without interpositional grafting.

The first manoeuvre is to stabilise the skeleton. The bone ends may need shortening if dead bone is present, or to assist primary repair of nerves, vessels or musculotendinous units. The method of bone stabilisation depends on several factors including which bone is involved, the fracture configuration and the condition of the overlying soft tissues. The chosen procedure should usually be the most rapid that is consistent with acceptable fixation of the fracture. Rarely, in major amputations, if the fixation is expected to become a lengthy process, a temporary vascular shunt may be used to reduce ischaemia time and maintain a healthy muscle mass. Alternatively a temporary, rapid method of fixation may be used with the intention of later revision.

The sequence from then on depends on whether the amputated part has a significant muscle component. If not, as for instance in a four finger replant at metacarpophalangeal joint level, all non-vascular structures are repaired first for technical ease, then the veins are repaired and finally the arteries. If there is a significant muscle component, ischaemia time and a complicating reperfusion injury are the main concern. Under those circumstances, vessels are repaired first (artery then vein) and all other structures are repaired subsequently. This is considerably more difficult and usually involves substantial blood loss. In such cases all compartments must be released by fasciotomy prior to reperfusion.

All vessels should be inspected microscopically for intimal damage and any areas of suspicion resected. If direct anastomosis is not possible without tension a vein graft should be used to reconstruct the defect. Alternative methods of vessel reconstruction include extra-anatomic bypassing or, in the hand, the re-routing of vessels from adjacent digits, such as the veins from neighbouring digits. However, Moleski found the morbidity in the donor digit associated with this technique unfavourable.

Fasciotomies are mandatory where the amputated part has a muscle component, as ischaemia time is always significant no matter how efficient the managing team has been. Skin closure should not be completed unless it is tension-free, and split thickness skin grafts may be necessary to cover areas of traumatic skin loss, or subsequently to close fasciotomy wounds.

**Post-operative care**

Just as elective free flap surgery depends upon both the technical skill of the team in theatre and the post-operative care the patient receives, the same is true for the patient who has undergone upper limb replantation.

In the post-operative period the patient should be nursed in a warm environment, be well hydrated and maintain haemodynamic stability. This key element of post-operative care maintains peripheral blood vessels in a relatively vasodilated state, which in turn maximises blood flow to the replanted part and decreases the risk of thrombosis in the anastomosed vessels secondary to low flow.

Pain is thought to result in peripheral vasoconstriction, and effective analgesia is essential. A regional anaesthetic block may be a useful adjunct in pain management, and has the additional advantage of encouraging local vasodilation by the blockade of the sympathetic nervous system.

Routine post-operative anticoagulation is not necessary in our experience (other than for appropriate prophylaxis against deep venous thrombosis) and should only be used where there is a specific indication in a given patient. We forbid smoking in the post-operative period because of the vasoconstrictive properties of nicotine, and the fact that smoke inhalation compromises blood oxygen saturation.

The monitoring of these patients should be undertaken by experienced, nursing staff, in a high dependency unit setting. Haemodynamic status can be monitored by measuring blood pressure, central venous pressure, pulse rate and fluid balance. Core and peripheral temperatures are measured (as a marker of peripheral vasodilation) with the difference being kept to less than 1°C by fluid balance manipulation.

Doppler ultrasound can be used, either as an external probe to assess distal pulses in the replanted part, or as an implantable probe attached via a sleeve to one of the anastomosed vessels (usually the vein). However, clinical observation is usually more important than any mechanical devices used for demonstrating blood flow. In replantation, unlike elective free tissue transfer, tibial temperature has been found to be a useful adjunct to clinical monitoring.

There is no substitute for experience and clinical judgement in both the nursing and medical teams following replantation. Several clinical signs such as colour, temperature, turgor, and capillary refill time can be used to assess the wellbeing of the replanted part. The signs that indicate either arterial or venous compromise are different (see below).

<table>
<thead>
<tr>
<th>Clinical findings in a failing replant</th>
<th>Arterial problem</th>
<th>Venous problem</th>
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<tbody>
<tr>
<td>Colour</td>
<td>Pale</td>
<td>Purple or bluish, fixed staining may occur</td>
</tr>
<tr>
<td>Temperature</td>
<td>Cool</td>
<td>Normal or increased</td>
</tr>
<tr>
<td>Turgor</td>
<td>Reduced, flaccid</td>
<td>Swollen, congested</td>
</tr>
<tr>
<td>Capillary refill time</td>
<td>Slow</td>
<td>Fast initially, slow later</td>
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Re-exploration should be done as a matter of urgency if there is any uncertainty about the patency of the re-anastomosed vessels, as prolonged periods of ischaemia or venous congestion will endanger the survival of the replanted part and may place the patient’s general status at risk.
Functional outcomes

Functional results have improved significantly over the decades in both adults and children, key developments being better microsurgical equipment, increasing surgical experience and the development of large microsurgical centres. This has been most apparent in crush and avulsion injuries, which were once considered a contra-indication to replantation—now evidence suggests useful salvage rates of 90% are achievable in even these severe type injuries. Loss of sensibility and cold intolerance are significant sequelae of replantation. It has been suggested that the severity of these symptoms can be correlated to the degree of vascularity of the replanted part, reflected by pulse pressure measurement. This is controversial, as cold intolerance is a common finding following any hand injury, although a strong correlation has also been shown with sensory nerve involvement.

Replantations at, or proximal to, the level of the wrist have a variable functional prognosis. The best results are at the wrist and distal forearm level. This correlates to Chuang

Figure 4 (a, b) The appearance and radiographic findings of a patient after amputation of all digits except the thumb. Note the different levels of injury in each digit. (c) The fixation of the bone with plates and screws illustrates the principle of transpositional digital replantation, with the more competent amputates placed on the most competent stumps. (d, e) The appearance of the hand prior to discharge showing good range of movement of the fingers and valuable hand function.
levels I and II, where the forearm muscles remain innervated and distal sensibility recovers well. The worst outcomes are seen after replantation at the proximal part of the forearm and elbow, which correlate to levels III and IV, where the forearm muscles are denervated at the time of injury and recovery of distal sensibility is poor. Battison highlights this finding by achieving a good result in 75% of patients undergoing replantation distal to the elbow level but in only 33% of patients undergoing replantation through the elbow or arm. Interestingly, in this series no patient, even the ones with poor functional results, requested a secondary amputation. Other studies have also shown patients fare better with replantation over prosthesis.

The thumb has a significant role in hand function and therefore replantation should always be attempted where possible.

Figure 5  (a, b) The hand after amputation of the right thumb, just distal to the metacarpophalangeal joint. Note the time of injury (19.30) and the start time of the operation (09.00 the following day), illustrating the principle that the microsurgical replantation of parts not containing large amounts of striated muscle may be deferred until suitable facilities and surgeon are available, provided the part is correctly preserved without cryodamage. (c, d) The amputated right thumb with the vessels at the cut edge inspected and tagged with suture material ready for anastomosis. (e) A vein graft, taken from the ipsilateral forearm. (f, g) The appearance immediately after replantation of the thumb. Excellent function was achieved after nerve regeneration and rehabilitation.
Figure 6  (a) This girl caught her hand in a thermal press that gripped her palm at 160 °C for 2 min. This poor quality polaroid image shows a hand on admission with blue ischaemic digits distal to a crushed palm in which all structures including the endosteal cavity of the metacarpals have been thermally coagulated and killed. (b) The right hand stump after debridement, covered with an ipsilateral pedicled groin flap. This flap was chosen for ease and speed, in view of the need to replant ectopically the salvageable digits. (c) The appearance 8 months after ectopic implantation of the central three salvageable digits onto the radial artery axis of the contralateral arm. This was necessary the night of injury to bank the digits since the debrided hand stump was not suitable for immediate replantation. The ectopic replantation has been designed with end-to-side anastomoses to the radial artery and vein to allow all digits to be raised on a single microsurgical vascular pedicle when the time comes to restore them to the hand. (d) The digits are now ready to be restored to the hand. They have been raised on the radial artery pedicle and the profundus tendons replaced by silastic rods to enable rehabilitation of the extensors before secondary graft reconstruction and rehabilitation of the flexors. At the same time a second toe microsurgical transfer is used to reconstruct the thumb. (e–g) Appearance of the reconstructed hand after all transfers are complete and tendons are rehabilitated, showing useful range of movement and function, with acceptable aesthetics. The thumb has been reconstructed from a second toe transfer and the pigmented skin of the original groin flap is clearly seen. This hand has substituted the original proximal phalanges for the destroyed metacarpals, and demonstrates the worth of individualising replantation solutions after complex trauma.
possible. Although most patients who have suffered thumb amputation are able to cope with activities of daily living, those with replanted thumbs have the benefit of opposition, a greater range of prehension patterns and a cosmetically more acceptable hand. In multiple digital amputations, all salvageable digits should be replanted. Where not all digits are available, amputated parts should be replanted to the most useful stumps or in orientations most likely to succeed to ensure maximal function. Reconstruction of the thumb, followed by a digit on the ulnar side of the hand, would enable functional prehension to be preserved, and so leave the patient with the most useful hand possible (Fig. 4).

Urbaniak et al. looked at a group of patients with single digit amputations and found proximal interphalangeal joint function (PIPJ) was highly dependent on the level of amputation in relation to the insertion of the FDS tendon. If the amputation was distal to the insertion of the tendon then the average range of motion of the PIPJ was 82° but this was reduced to 35° if the amputation was proximal to the FDS insertion. Overall, hand function was the same or improved in the former group but significantly worse in the latter. Therefore, Urbaniak advocates single digit replantation in those with amputations distal to FDS insertion.

In fingertip amputations there is evidence that replantation gives a superior functional and aesthetic result to terminalisation of the stump. These benefits include increased range of movement at the PIPJ (and subsequent improvement in fine dexterity), a lower frequency of pain and better cosmetic results. Patient satisfaction has also been shown to be higher in patients who undergo replantation.

Replantation in children

Amputations in children are rare but the results of replantation are good (Fig. 5). Although considered technically more challenging than reimplants in adults, experienced microsurgical centres record replant survival rates of 97%. Cheng’s series highlights the excellent functional recovery that might be expected in a child following digital replantation; the range of movement achieved is excellent (better than might be expected in an adult), a normal 2-point discrimination is seen in 88% of cases and in all cases there is normal capacity for, or only minor limitation in, activities of daily living. Such excellent results are due to several factors:

- Children are physiologically resilient.
- There is a low rate of acquired co-morbidity.
- Rehabilitation is intuitive.
- Dissembling and malingering are rare.
- Regenerating distances are shorter and forces of motion lower.
- Nerve regeneration is better.
- Adhesions and scarring can be overcome by axial growth.

As the functional results are so good, and because of the special cosmetic considerations in a child, all upper limb amputations in children should be replanted if possible. This is with the caveat that occasionally growth may be impaired, which in turn can result in a poor outcome.

Ectopic replantation

Ectopic replantation is a technique that deserves special mention as a reconstructive alternative when immediate replantation is unlikely to succeed due to severe tissue damage. This technique also has the advantages of preserving limb length and shortening the operative time of the initial operation when the patient may be physically unstable or the stump unsuitable for accepting the replant. Although the circumstances for use are rare, the senior author has found this technique useful in a case where a hand was trapped in a plastic heat press at a temperature of 160° for a prolonged period (Fig. 6). This resulted in a severely crushed palm with heat coagulation of all structures therein, but uninjured digits distally. These digits were ectopically replanted onto the contra-lateral forearm while the amputation stump was debrided and resurfaced with a pedicled groin flap, preserving as much length as possible. The final outcome after replantation of the digits, and a free toe transfer to reconstruct the thumb, was a hand that gave the patient a good level of function and a cosmetic result preferable to an amputation.

Conclusion

Upper limb amputation is a potentially life-threatening injury which requires at least one major operation, with long-term rehabilitation and follow-up. The management of patients with such injuries should take place in experienced microsurgical units where all options are available and decision making is based on experience and considers the patient’s wishes and consent in the context of the likely functional and aesthetic outcome. It has been shown that appropriate and competent replantation can achieve not only a viable limb, but also a functionally useful limb. This is the goal we should strive for when a patient presents with an upper limb amputation, and is a genuine reality in today’s surgical workplace.

Reference


