Replantation

William C. Pederson, M.D.
San Antonio, Texas

Learning Objectives: After studying this article, the participant should be able to: 1. Describe the indications and contraindications for extremity replantation. 2. Outline the sequence and technique of replantation. 3. Identify potential complications of replantation and recognize treatment options. 4. Assess the results of replantation in terms of function and costs versus benefits.

The ability to microsurgically re-attach a body part that has been amputated represents one of the pinnacles of reconstructive surgery. Replantation of such parts offers a result that is usually superior to any other type of reconstruction. However, replantation of extremities involves more than microsurgery, as repair of bony and tendon injury must be undertaken as well. This article will focus on the indications, technique, and results of replantation of amputated body parts.

EXTREMITY REPLANTATION

History

The first successful replantation of a severed limb was carried out nearly 40 years ago by Malt in Boston when he replanted the completely amputated arm of a 12-year-old boy.¹ Revascularization of incompletely severed digits was proven feasible in the clinical setting by Kleinert and Kasdan in 1965.² The first successful digital replantation was performed by Komatsu and Tamai in Japan, as reported in this Journal in 1968.³ Since these early reports, replantation of extremities has become an accepted procedure,⁴–⁸ and the indications, technique, and expected results will be discussed below.

Indications

Although the indications for replantation have not changed significantly over the years, experience with the techniques and results has refined these indications (Table I). All indica-

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<th>Indications for replantation</th>
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<tr>
<td>Thumb</td>
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<td>Multiple digits</td>
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<td>Hand amputation through palm</td>
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<td>Hand amputation (distal wrist)</td>
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<td>Any part in a child</td>
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<td>More proximal arm (sharp only)</td>
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<td>Finger distal to sublimis insertion (zone I)</td>
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<th>Contraindications for replantation</th>
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<td>Single digits proximal to flexor digitorum superficialis</td>
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<tr>
<td>insertion (zone II)</td>
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<tr>
<td>Severely crushed or mangled parts</td>
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<td>Multiple-level amputations</td>
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<td>Replantation in patients with multiple trauma or severe</td>
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<td>medical problems*</td>
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* Relative contraindication.

tions for replantation must take into account the status of the amputated part (sharp amputation versus crush) and the patient (healthy versus systemic illnesses.) The degree of tissue injury may militate against replantation, even in the case of a clear indication, such as thumb amputation. The indications are not based solely on potential viability but are predicated on the potential for long-term function. Overall, thumb replantation probably offers the best functional return. Even with poor motion and sensation, the thumb is useful to the patient as a post for opposition⁹–¹² (Fig. 1). A replanted thumb offers the best reconstruction available, toe transfers notwithstanding. Although single-finger replantations are generally not performed¹³,¹⁴ (see contraindications below), replantation beyond the level of the

From the Hand Center of San Antonio and Departments of Surgery and Orthopaedic Surgery, the University of Texas Health Science Center at San Antonio. Received for publication February 25, 2000; revised August 7, 2000.
sublimis tendon insertion (zone I) usually results in good function\textsuperscript{15,16} (Fig. 2). Multiple finger amputations present reconstructive difficulties that may be difficult to correct without replantation of one or all of the amputated digits.\textsuperscript{13,17} Any hand amputation from zone III (distally) to zone V (proximally) offers the chance of reasonable function after replantation, usually superior to available prostheses.\textsuperscript{18–20} Although usually indicated, the replantation of any hand or arm proximal to the level of the mid-forearm must be carefully considered. The risk of complications goes up and the chance of functional return goes down with amputations above the elbow (see below). It is generally believed that replantation should be attempted with almost any part in a child. In children, success rates (in terms of viability) are lower, but the functional results are better.\textsuperscript{21–23} Although there have been several reports of successful lower limb replantation,\textsuperscript{24–29} this area remains controversial. The available lower extremity prostheses make amputation less of a functional problem in the leg than in the upper extremity. The leg contains larger masses of muscle (which tolerate ischemia poorly) and without adequate sensory recovery, the foot is at risk for soft-tissue breakdown. Replantation and revascularization of the foot, lower leg, or both, in children may give gratifying results, however.\textsuperscript{30–32}

**Contraindications**

The contraindications to replantation are more relative than the indications, but they must be kept in mind (Table I). Single-finger replantations at the level of zone II (from the A1 pulley to the distal sublimis tendon insertion) are rarely indicated, with the notable exception of the thumb. Amputated parts that are severely crushed and those with multiple-level injuries have poor function even if they survive replantation\textsuperscript{33,34} (Fig. 3). Patients with parts of fingers that have been completely degloved (ring avulsions) are generally considered poor candidates for attempted replantation\textsuperscript{35} (see below). Very distal amputations at the level of the nail bed are marginally indi-
cated, as there needs to be approximately 4 mm of intact skin proximal to the nailfold for adequate veins to be present (Fig. 4). Patients who have severe systemic injury or disease may not tolerate the anesthesia and surgery well, and the consideration of replantation in these patients must weigh systemic risks versus the potential functional loss of the amputated part. Successful replantation has been reported in an octogenarian, but the functional results were poor. Experience in patients who have severe mental disease or suffer from substance abuse may also be poor. Although the technical aspects of replantation in these individuals may not present a problem, postoperative compliance is usually poor and rehabilitation difficult. With appropriate postoperative support, however, reasonable functional results are possible.

Patient Management

Although replantation can be successfully performed in a community hospital, patients suffering from extremity amputation are often transferred to a center that performs these operations routinely. Before transfer, the patient should be stabilized cardiovasculally and the amputated part cooled to maximize its ischemic tolerance. The part should be gently cleansed, but attempts at debridement in the emergency room should be avoided. The part should be wrapped in a moist gauze sponge, placed in a container (either sterile bag or specimen cup), and then placed in ice. Floating the part in cold saline is probably not detrimental, but this method tends to macerate the tissue if it is in this solution for many hours. Dry ice is to be avoided, as it can freeze the part. The ischemic tolerance of amputated digits is fairly high, due to the lack of significant muscle mass. The warm ischemic tolerance of digits is generally believed to be in the range of 8 hours, but successful replantation has been reported after cold ischemia times of up to 30 to 40 hours and longer. With more proximal amputations, the ischemic tolerance is significantly shorter. The absolute maximum warm ischemic tolerance for major amputations is in the range of 4 to 6 hours, and this may be prolonged by cooling to the 10- to 12-hour range. Amputated parts with a significant amount of muscle (arms and legs) have very poor ischemic tolerance, and delay in replantation can lead to significant metabolic problems after revascularization.

Once the patient arrives, preparation for surgery should proceed rapidly. Repeated examinations of the injured limb should be avoided, as this is painful and may increase the risk of vascular spasm. The patient should be warmed, and intravenous solutions administered to keep the blood volume and pressure up. X-rays are taken of the amputated part and the limb suffering the amputation. X-rays of both are important, because there may be missing bony fragments, and management of this should be planned for and discussed with the patient. The patient is given broad-spectrum antibiotics and tetanus prophylaxis when appropriate. The operative permit should include permission for at least the following: revision amputation, vein grafts, nerve grafts, skin grafts, bone grafts, and possibly free flaps for coverage.

Once the patient has been worked up in the emergency room, the part is taken to the operating room for examination and preparation. Careful examination of the part in the operating room before the patient is under anesthetic allows time for appropriate decision-making. After careful debridement, the digital vessels are dissected out and examined under strong loupe magnification or the microscope. The vessels must be examined very carefully, as their status can give an idea of the severity of injury and whether vein grafts will be needed (or in fact whether replantation can be attempted). A corkscrew appearance of the arteries (the “ribbon” sign) suggests that an avulsion force has been applied to them, and this segment of vessel should be excised and vein grafted. If bruising is noted along the course of the digit where the neurovascular

Fig. 3. Avulsed fingers from injury in farm machinery. Note crushing of part, multiple-level injury, and tendon avulsion—all militating against successful replantation.
bundle runs, this finding suggests a severe avulsion injury with disruption of branches of the digital artery at the sites of the bruises (Fig. 5). This particular sign should alert the surgeon that revascularization of the amputated part may be unsuccessful.

Once identified, the arteries and nerves are marked; it can be surprisingly difficult to find these later. A 6-0 polypropylene suture that is cut long serves this purpose well. If veins on the dorsal surface are obvious, these are marked as well, but they are often easier to find after completion of the arterial anastomosis. Attention is next turned to the bones and tendons. The bone should be minimally debrided with a curette and managed as an open fracture. Once the bone is cleaned, distal fixation can be placed in the amputated part. The type of fixation used depends on several factors, but in fingers, the simplest is usually the best. For this reason, crossed Kirschner wires are usually used and are placed retrograde in the amputated finger first. Interosseous wires can be used to supplement the Kirschner wires but are usually not necessary. Although plates can be used in digital replantation, these are more time-intensive and require extensive soft-tissue dissection for bony exposure. Plate fixation in replantation at the proximal phalanx level may be indicated to allow early motion, however. Plates offer excellent fixation in amputations through the mid-metacarpal level, and the distal portion of the plate can be placed on the amputated part in the preparation stage if attention is paid to alignment (relative to the site of amputation and amount of proximal bone available) (Fig. 6). Periosteal repair should be performed after bony fixation, particularly on the dorsal surface, to decrease adhesions of the tendons to the bone.
After placing the distal bony fixation, attention is turned to the tendons. These may need to be trimmed to give a clean end, but excessive trimming should be avoided. In zone II, it may be best to repair the profundus only, especially if the tendons are not cut cleanly. A double core suture technique is usually chosen for the flexor tendons, and half of this suture can be placed in the distal tendon before final bony fixation.

**Surgical Technique**

At this point, the amputated part is ready for replantation and the patient should be under anesthetic with the injured limb prepared. The amputated part is kept on ice while the amputation stump is made ready. The stump is irrigated with antibiotic containing saline solution and nonviable tissue and debris is removed. The proximal bone is minimally debrided, and small loose bony fragments are removed. Larger fragments should be cleaned and saved for use if necessary. The tendons, vessels, and nerves are exposed and made ready for repair. These can be exposed through a Bruner-type zigzag incision in the finger or palm. Once these structures are identified, the amputated part is brought into the field and bony fixation completed. This step should proceed rapidly if the distal fixation was properly done. After bony fixation, the tendons are repaired in standard manner, using the previously placed core suture for the flexor tendon(s).

Patients undergoing replantation whom have suffered avulsion of the digit with attached tendon should all have release and exploration of the carpal tunnel. As the finger is pulled out, portions of the muscle belly may be avulsed within the carpal tunnel, leading to acute median nerve compression (Fig. 7). As this condition is difficult to diagnose in a patient after replantation surgery, release of the transverse carpal ligament and removal of nonviable muscle fragments should prevent compression of the median nerve. In these individuals, consideration should be given to performing a forearm fasciotomy as well, as swelling can ensue postoperatively because of the trauma of avulsion of the tendon from muscle—especially if the patient is heparinized.

If the total ischemic time has been short,
nerve repair should be done next. If the surgeon is concerned about ischemia, then arterial repair takes precedence over nerves. The function of replanted digits is much better if return of sensibility is reasonable, and special attention should be paid to nerve repairs. The edges must be trimmed back to undamaged nerve, and doing this adequately may not allow primary anastomosis. Nerve gaps should be grafted in most digital replants, unless the likelihood of survival is believed to be low. In the case of a multiple-digit amputation, the most damaged finger may prove useful as a source of parts to repair the other digits—especially nerve and skin grafts. Other sources of nerve graft include the medial antebrachial cutaneous nerve from the forearm and the sural nerve. In any case, the finger should not be flexed to allow primary nerve anastomosis, as later movement will likely disrupt this repair.

The vascular repairs are done next. Although primary repair of the arteries is occasionally possible, vein grafts should be used if any question about the status of the artery exists. The vessel should be trimmed back until there is no thrombus or intimal separation. Vein grafts of appropriate size for digital arteries can be harvested from the distal volar forearm or dorsal foot. If there is volar skin loss and coverage of the neurovascular repairs will be a problem, some skin overlying the vein graft may be taken with the vein graft, and this unit used as a small flow-through venous flap. This method will obviate the need for skin grafts or another type of flap later. After arterial repair, the finger should rapidly “pink-up,” but this may take a period of 10 to 15 minutes if the digit is cold or there has been a long ischemia time. Four percent Xylocaine, papaverine, or both, placed on the vessels will minimize vasospasm, and the finger should be wrapped with warm sponges after arterial repair is complete. One should wait 10 to 15 minutes and watch the status of perfusion before repairing veins. If the finger does not show signs of good perfusion after this period, revision of the anastomosis is in order or a second arterial repair performed. Many studies have shown that survival rates are improved with the anastomosis of two arteries per finger; however, a single anastomosis with good flow may be adequate.

Thumb amputations present certain technical difficulties in terms of vascular anastomosis. With amputations between the metacarpophalangeal and interphalangeal joints, access to the arteries can be difficult after bony fixation. For this reason, most authors suggest the use of a vein graft from the radial artery in the anatomic snuffbox to the amputated segment, particularly in avulsion injuries. Anastomosis of the vein graft is performed first to the distal vessel on the amputated part (usually on the back table), followed by proximal anastomosis after bony fixation.

There should be brisk bleeding from the veins after the digit is warmed up, and one should select the two veins that are bleeding the most for venous anastomosis. Due to the anatomy of the dorsal venous system, it is less common to need vein grafts for venous outflow. The veins are exposed by carefully elevating the dorsal skin off of the venous plexus, and division of one or more branches will usually provide a gain in length to allow primary anastomosis. If primary anastomosis is not possible, vein grafts should be used. This will often be the case in patients with dorsal skin loss, in which case either a venous free flap or a long venous pedicle flap from an adjacent finger may be necessary. Once adequate length for primary anastomosis has been gained, the two veins with the most brisk bleeding should be connected. All other bleeding veins should be identified and closed with small vascular clips or with the bipolar cautery, which will maximize flow by means of the anastomosed veins. In some instances, there may not be adequate veins for anastomosis (especially in very distal replantation.) If brisk retrograde flow is noted in the contralateral digital artery after repair of one artery, the
second artery can be anastomosed to a proximal vein to provide outflow for blood.

If arterial and venous flow is adequate at this point, the skin should be closed carefully. Care must be taken to avoid compression of the veins by skin closure, and a minimal number of sutures should be used. If any question exists as to whether the skin closure will be too tight, small nonmeshed split-thickness skin grafts should be placed. It is far better to place a small skin graft over the draining veins than to occlude outflow by a too-tight skin closure. The extremity should be placed in a well-padded splint with no circumferential dressings around the digits. An excellent dressing can be made by wrapping the entire extremity in 1-inch foam, which is then wrapped with plaster rolls. This type of dressing cannot become too tight in the postoperative period.

**Postoperative Management**

The patient should be placed in a warm room in the postoperative period. Arterial spasm can be a significant problem in replanted digits, and keeping the environment warm may lessen this problem. An indwelling axillary sheath catheter should be placed in the operating room, through which a constant infusion of Marcaine is given to provide both pain relief and a chemical sympathectomy. Its use is certainly indicated if vascular thrombosis occurs in the operating room or the vessels appear severely damaged. Chlorpromazine is a potent peripheral vasodilator and is given orally in the dose of 25 mg three times a day for this effect and its sedative action on the patient for 3 to 5 days postoperatively. Aspirin is also given at a dose of 325 mg daily for its antiplatelet effect. This aspirin dose is generally given for a total of 3 weeks postoperatively.

Unless there is a circulatory problem, the replanted part should not be manipulated in any way in the immediate postoperative period. Except in the case of major limb replantation, all wounds should be closed at the time of initial replantation. Experience has shown that an early return to the operating room with blood pressure shifts from anesthesia and temperature change can lead to irreversible vascular spasm. Problems can also be encountered after dressing changes in the first few days postoperatively, which should be avoided. When the patient is ready to be discharged, the outer splint and dressing can be removed, but any adherent dressing next to the wound should be left in place.

**Ring Avulsion**

A special case of digital amputation involves ring avulsions. In this injury, the soft tissue is partially or totally avulsed from the underlying bone and tendon. Urbaniak has classified these ring avulsions into three types (see Table II). Management of type I is fairly straightforward, as neurovascular injuries are dealt with in standard manner. There may be significant damage to the soft tissues in type II, however, and coverage of the vascular repairs may be necessary (Fig. 8). As noted above, a small venous flow-through flap or some type of local flap from the hand can be used for arterial repair, venous repair, or both, in these instances. The management of type III ring avulsions remains somewhat controversial. Most authors agree that replantation of the completely avulsed skin envelope is often unsuccessful, and even with a successful revascularization of the skin, function is usually poor. Thumb avulsions, on the other hand, should be considered for replantation. If successful, this type of replant usually gives better function than an amputation. Experienced authors believe that the best management of patients with type III ring avulsions and those with amputation proximal to the sublimis insertion may be primary ray amputation of the finger (Fig. 9). This approach gives both a very functional and cosmetic result, whereas a poorly functioning “replantation” of a completely avulsed digit may interfere with global hand function.

**Monitoring**

The primary problem with any technique for monitoring vascular flow is that it must be interpretable and understood by the nursing staff. There are several excellent techniques for monitoring the status of tissue perfusion today, but many of them suffer from technical difficulty.

**TABLE II**

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<th>Type</th>
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<td>I</td>
<td>Soft-tissue injury only, no vascular compromise</td>
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<tr>
<td>II</td>
<td>Soft-tissue injury with arterial and/or venous compromise</td>
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<td>III</td>
<td>Total degloving of soft tissues</td>
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culties and problems with interpretation. For this reason, many surgeons prefer to monitor the vascular status of replanted digits with temperature measurement.85–88 In general, the temperature of a well-vascularized digit should be at or above 31°C.89 Although temperatures somewhat below this may be compatible with adequate inflow, a decrease in arterial inflow will result in a rapid loss of temperature in the digit. The baseline after surgery should be noted, and any marked decreases in this temperature indicates problems with the artery. Another monitoring technique is the use of a pulse oximeter.90,91 This probe can be placed on the distal digit, and changes in inflow will give a rapid change in oxygenation. Laser Doppler flowmetry has also found some advocates, and if the equipment is available, this technique is very sensitive to changes in arterial flow.86,92,93 Photoplethysmography monitoring has been advocated in the past,94 but the interpretation of these data may be difficult for nursing personnel and has largely been supplanted by the above techniques.

Management of the Failing Replant

There has been much discussion on the approach to the best management of a replanted extremity that is having vascular difficulties. The only sure way to remedy a vascular problem with a replanted part is to revise the anastomosis. The decision to take a patient back to surgery for salvage depends on the circumstances involved in the injury and findings at surgery. Reported success rates of reoperation for vascular salvage of compromised replants range from 9 to 89 percent.21,61,63 Some experienced surgeons believe that the initial surgery should be the “best” that can be done, and rarely return to surgery to attempt secondary repair of thrombosed vessels (Urbaniak, personal communication). This attitude is certainly applicable to digits, and experience shows that fingers that struggle to survive (with or without vascular revision) are usually functionally the worst. They are often atrophic, have poor sensation, and move poorly. Although a thumb with these attributes may be useful to the patient, digits like this are rarely useful. Replanted hand parts certainly deserve reexploration if they show signs of vascular compromise, and replantations in children should usually be reexplored if problems arise. In the case of severe avulsion and/or crush injuries, more proximal amputations, and patients who have suffered perioperative systemic complications, a return to surgery for attempted salvage may not be appropriate.

Nonoperative treatment may improve the situation and, in fact, lead to salvage of some compromised replants. If arterial inflow decreases, the dressing should be loosened and the patient should be heparinized (if not already on heparin). Likewise, an axillary block may improve the situation if vascular spasm is present. If a decrease in arterial flow occurs, however, the primary decision is whether to return the patient to surgery or not—knowing that reoperation is the option of choice if the digit is to be salvaged.

Venous outflow problems present a somewhat different set of considerations. Distal digital replantation (at or beyond the distal interphalangeal level) may not have adequate veins for reanastomosis.95–97 This type of replant may be appropriate in some patients, and venous
outflow may present difficulties. An arteriovenous anastomosis can be performed to the other digital artery in some patients, but failing this, there must be some provision for venous outflow. Some authors have proposed heparinizing the patient and removing the fingernail. A heparinized pledget is placed on the nail and this is removed at intervals to promote bleeding. My experience with this technique has been less than satisfying. A second, and usually more reasonable option, is the use of leeches.

The medicinal leech, *Hirudo medicinalis*, secretes a complex protein anticoagulant called hirudin. Its action is largely local, and systemic side effects are minimal. In the replant with venous outflow obstruction, leeches can provide adequate outflow to allow survival of the part. It is common to see the statement that leech therapy is only necessary for 2 or 3 days, but this is certainly not the case in my experience. If there is total obstruction of venous outflow, near-continuous leeching will be necessary for at least 5 to 6 days, and the patient may suffer significant blood loss (in the 2 to 6 unit range.) This blood loss represents the primary potential complication of leech therapy, but they also have the potential to cause infection. *Aeromonas hydrophila* is a saprophytic organism in the leech’s gut, which, although not a primary pathogen in humans, can cause significant infection. One review article found that infection occurred in 7 to 20 percent of cases of leech application for venous outflow problems and was associated with a decrease in salvage of the involved tissue. Infection is uncommon in tissue with adequate arterial supply, however, and their use should be avoided if the viability of the tissue is questionable. To minimize the risk of infection, the patient should be covered with appropriate antibiotic therapy during the period of leech application. Studies of leech flora suggest that a third-generation cephalosporin is appropriate prophylaxis in most cases.

Complications

Serious complications are unusual in digital replantation, and are usually related to the patient’s underlying health rather than the surgery itself. The primary operative complications include bleeding (usually from anticoagulation), infection, and loss of the replanted digit. If serious bleeding is encountered, the value of the replanted part versus the potential side effects of transfusion should be weighed and discussed with the patient. Infection after digital or hand replantation is unusual and is usually related to the amount of contamination and adequacy of debridement. However, the presence of infection can lead directly to vascular thrombosis and loss of the digit or digits. This fact emphasizes the necessity for good initial debridement and coverage with vascularized tissue.

If the initial replantation is successful, late problems are usually reflected in poor motion and function of the replanted part. Nonunion is uncommon, but has been reported. The joints may undergo Charcot change due to denervation, but this is surprisingly uncommon. Late necrosis of the replanted part may occur, particularly if there is poor soft-tissue coverage or infection occurs.

Secondary Surgery

The need for secondary surgery after digital replantation is common and is usually related to poor sensation or motion. Neurolysis or nerve grafting may be required, particularly if the nerves were not repaired at the initial setting. Tenolysis is frequently necessary, as early motion is not possible in most patients undergoing replantation. This has been shown to be a valuable procedure in postreplant patients (Fig. 10). Tenolysis may be necessary on both the flexor and extensor sides of the digit, as the extensor tendons will often become adherent at the site of bone injury. In some cases, staged reconstruction of the tendon by placement of a Silastic rod followed by tendon grafting may be necessary. Webspace release and flap coverage may be needed in patients with thumb replantation if first webspace contracture is not prevented. Request for amputation of a replanted digit by the patient is unusual, even if function is poor.

Major Limb Replantation

As noted above, replantation of more proximal amputations are indicated in certain situations. The function of hands replanted from the mid-metacarpal level to distal wrist (zone III to zone V) is usually quite good, although intrinsic muscle function is usually poor. More proximal amputations though the muscle bellies of the flexors and extensors can function well, but are often avulsion injuries, which may severely compromise later function. Amputations above the elbow should be considered for
replantation in certain instances, but the main goal is often preservation of a functioning elbow for later prosthesis fitting. Ischemia time is very important in proximal amputations, as the large amount of muscle mass in these amputations tolerates ischemia poorly. Attempting to replant a forearm or arm with a prolonged warm ischemic period can lead to severe metabolic problems and potentially death of the patient. Debridement of nonviable tissue is paramount, and this process leads to the problem of soft-tissue coverage in many of these patients. Although uncommon in digital replantation, infection, and even systemic sepsis is the number one complication in major limb replants. For this reason, major limb replantation is not to be undertaken without a serious commitment to the endeavor.

Technically, there are a few points about major limb replantation that should be noted. Stable bony fixation is very important, to maximize healing and avoid motion that could disrupt vascular repairs. However, the usual sequence of surgery should be modified, because revascularization of the ischemic muscle is paramount. Some allow arterial perfusion by means of a shunt, which is used to perfuse the amputated part while bony fixation is performed. A vein graft can also be used, if it is made long enough to allow manipulation of the bone. While the part is receiving arterial blood, the venous effluent is simply allowed to bleed out. For this reason, every patient who is to undergo an attempt at major limb replantation should be typed and cross-matched for multiple units of blood and informed that blood transfusions will be required.

For forearm and transhumeral amputation, most prefer bony fixation with a plate. If there is significant bony comminution or loss, an external fixator can be used, particularly in the forearm. This method will allow stabilization of the bone fragments while vascular and soft-tissue repair is undertaken, with bony reconstruction planned for a later date if the initial procedure is successful. Once the bone is fixed, vascular repair can be done. If an arterial shunt has been used during this period, the artery is repaired first. Vein grafts are often required, unless there is significant bony shortening, and should be used if any question as to damage to the vessel ends exists. The approach to nerves should be individualized. Without return of sensation, the part replanted will be virtually useless, but unless there is good soft-tissue coverage and a high likelihood of success, primary nerve grafting of long gaps is probably not indicated. If the replant is successful, nerves can be prioritized and grafted in a good bed when the wounds are healed.

The final (and often most important) issue in these cases is management of the soft-tissue loss. Local tissue is rarely available for coverage of bone and neurovascular repairs; thus, regional flaps or free flaps may be needed. The latissimus dorsi can be very useful as a pedicled flap.

Fig. 10. (Above) Little finger amputation in 5-year-old. (Center) Flexion at 6 months. (Below) Improvement in flexion after flexor tendon tenolysis.
flap for coverage of the upper arm, and the pectoralis major may be useful in smaller, more proximal defects. However, for most forearm injuries, a free flap will be required for significant soft-tissue loss. Many believe that wound coverage should be obtained at the time of replantation, as exposed bone and neurovascular structures will fare poorly if not covered with well-vascularized tissue. When the vascular repairs are performed, vein grafts can be taken longer than needed and placed in an extra-anatomic position if necessary to avoid exposure.

For coverage of these wounds, muscle is probably the best choice in terms of vascularity and resistance to infection. The surgeon can choose whatever muscle he is most comfortable with, but adequate tissue should be transferred to fill dead space and afford coverage of deep structures. Although thorough initial debridement is vital to success, all patients undergoing major limb replantation should be considered for return to the operating room at 24 to 48 hours, to evaluate the wound and further debride nonviable tissue if necessary. For this reason, initial muscle coverage should allow extra tissue if this debridement becomes necessary at the second look, at which time extra tissue can be removed if necessary. All patients with proximal replantation should have fasciotomies of the hand and forearm, as the usual clinical parameters of compartment syndrome (pain and sensory changes) will not be present in a replanted limb, and an untreated compartment syndrome in the replanted limb will render it useless. Secondary surgery is almost always necessary in major limb replantations and can range from muscle/tendon transfers to nerve grafting.

RESULTS

Successful revascularization of the amputated part should be expected in up to 80 percent of cases. However, success is not measured today by survival. Function is the only real measure of success, and based on this, success can often be predicted by the level of amputation. Single fingers distal to the sublimis insertion usually function well, even without motion at the distal interphalangeal joint. Hands proximal to the mid-palm also usually function very well (Fig. 11). A replanted thumb is almost always useful, even if it functions as a post for opposition, and is certainly the “best” reconstruction available. However, a recent study compared hand function after thumb amputation and replantation and found little significant difference between the two groups. Patients with more proximal amputations and those with crush or avulsion injuries will often have poor functional return. Function is usually predicated on the quality of sensory return; thus, return of sensation is important. The average sensation of replanted thumbs is approximately 11 mm, with clean amputations having better sensation and avul-

![Fig. 11. (Above) Hand immediately after replantation at metacarpal level. (Center) Dorsal view at 8 months (3 weeks after Z-plasty of scar). (Below) Flexion at 8 months.](image)
sion injuries poorer. The average two-point discrimination of sharply amputated fingers averages 8 mm, with only 15 mm in patients suffering crush-avulsion type injuries. Sensation is always better in children than adults. Motion is usually rather poor, with only approximately 35 degrees of motion in proximal interphalangeal joints replanted proximal to the flexor digitorum superficialis insertion. This motion improves to 82 degrees when the amputation is distal to the flexor digitorum superficialis insertion. Cold intolerance is a problem in all patients after replantation, and although most believe that this improves after approximately 2 years, some studies have shown that this persists for many years. The improvement in cold sensitivity is usually related to the quality of sensory reinnervation, and patients with better sensation usually have less cold intolerance.

Cost versus Benefit of Upper Extremity Replantation

Questions have been raised about the cost-effectiveness of replantation. In a study from Israel, Engel et al. found that any amputation that would result in greater than a 15 percent impairment of the hand would benefit from replantation. Based on the 4th edition of the AMA Guides to the Evaluation of Permanent Impairment, loss of the thumb at the interphalangeal joint results in a 20 percent impairment of the hand, and loss of the index or middle finger at the proximal interphalangeal joint leads to a 16 percent impairment. These statistics would certainly suggest that digital replantation is cost-effective, if one applies the values from Engel et al.’s study. Another study from Sweden found that replantation was twice as costly as amputation, and that half of these costs were due to nonsurgical factors, primarily rehabilitation and the costs of time off work. A study from Austria, on the other hand, found that 82 percent of patients undergoing replantation had compensation benefits lower than those that would have accrued with amputation of the part. Although it is difficult to say exactly how these data compare with those of the United States, one would have to assume that replantation is valuable not only to the patient but to society as well in terms of cost.

Lower Extremity

Amputation of the lower extremity is usually secondary to severe trauma, and because of the crushing nature of the injury, replantation may not be a viable option. Even without total amputation, foot salvage in the presence of severe crushing injuries to the lower leg remains a controversial issue. The conditions that favor consideration of replantation of the lower extremity are amputations in young healthy patients, sharp amputations, and those in the distal third of the leg. The contraindications for lower extremity replantation mirror those of the upper extremity and include life-threatening associated injuries, crushing or avulsion injuries, and age or chronic illness that would preclude a prolonged operation. The time period of ischemia is also a critical consideration, as prolonged ischemia predicts against success of replantation. A significant ischemic period in this group of patients may lead to myonecrosis and renal failure if attention is not paid to this issue. These patients will all require transfusion, with an average of 15 units in one series. However, with sharp amputations in young patients, results can be quite good. Many patients will require further surgery after successful lower extremity replantation, particularly in the presence of major limb length discrepancies.

Although replantation of the great toe has been reported in children, this procedure is probably rarely indicated in adults. However, replantation of the heel pad has been reported with good results. Larger portions of the foot can be replanted with acceptable function if the amputation is sharp. With a crushing amputation of the lower leg, problems may arise in terms of coverage of the stump to maintain a functional length for prosthesis fitting. In cases such as this, portions of the foot may be replanted to cover exposed bone in the stump. The plantar surface of the foot has been used for this purpose and is nicknamed the “fillet of sole.” The dorsal surface can also be transferred based on the posterior tibial/dorsalis pedis system. Use of this otherwise discarded tissue provides excellent coverage and obviates the need for distant flap transfer.

Nonextremity Replantation

Microsurgery had been used for replantation of several tissues that have been amputated or avulsed. Among those reported have been the ear, the nose, the lip, the scalp, and even the entire face. There
have also been several reports concerning replantation of the penis,\textsuperscript{165}–\textsuperscript{165} amputation of which is often the result of self-mutilation. Although patients presenting with the need for replantation of facial or other body parts are unusual, these types of replantation will be discussed below, with particular emphasis on the problems encountered.

**Ear Replantation**

Loss of the ear from trauma presents a significant reconstructive challenge, and the replantation of an ear obviates the problems associated with its loss. Ear replantation presents some formidable difficulties, primarily because of the size and number of vessels. The primary arterial supply (relative to vascular repair) is from the temporal artery. There is a small branch from the temporal at about the level of the tragus, which supplies the anterior surface of the ear. This vessel is quite small, but primary anastomosis is possible by skilled microsurgeons. If the ear has been sharply amputated, this connection may be possible. Unfortunately, many ear amputations are secondary to avulsion, which may render primary repair impossible. In these cases, vein grafts may have to be used or, alternatively, the temporal artery can be freed up and brought posteriorly as a vascular leash for anastomosis to the ear.\textsuperscript{152} However, the real problem with ear replantation is the venous drainage. The veins on the posterior surface are extremely small and few in number. However, ear replantation can be successful without venous anastomosis and many authors suggest using leeches in lieu of vascular repair for venous drainage.\textsuperscript{166–169} Others suggest making stab wounds in the posterior ear to allow for drainage.\textsuperscript{151,170,171} All reports of successful ear replantation have used heparin. If vascular repair is deemed impossible or thrombosis occurs, the ear cartilage can be salvaged by wrapping it in the temporoparietal fascia.\textsuperscript{172} Because of the relatively few reports of ear replantation, success rates are difficult to estimate. However, with a successful arterial anastomosis and the use of heparin and leeches, success should be expected. Even with partial survival of the replanted ear, the cosmetic results are usually superior to reconstruction.

**Scalp Replantation**

Many cases of replantation of the scalp have been documented since the first such cases reported in this journal in 1978.\textsuperscript{159,173} As in the case of ear replantation, scalp replantation offers a result far superior to other types of reconstruction of this defect. The availability of vessels for anastomosis is related generally to the size of the avulsed portion of scalp. If the entire scalp has been torn off, there are usually vessels of reasonable size available (primarily the temporal),\textsuperscript{174,175} although vein grafts may be needed to bridge damaged segments.\textsuperscript{161,176,177} The entire scalp can survive on a single artery and vein if there is adequate flow through these vessels.\textsuperscript{178,179} The problems reported with scalp replantation include poor venous outflow, which may necessitate the use of leeches\textsuperscript{180} or incisions in the skin to allow venous bleeding.\textsuperscript{181} The use of a second artery in the scalp for anastomosis to a recipient vein to allow egress of blood has also been reported.\textsuperscript{161} Hematoma formation under the replanted scalp is one of the more commonly reported complications, and can lead to compromise of the tissue.\textsuperscript{182,183} The results in reported series has generally been good, with only approximately a 5 to 10 percent total failure rate. However, “partial” loss of the tissue is fairly common with approximately 30 percent of patients sustaining partial necrosis of the replanted tissue.\textsuperscript{161,177,183,184} The need for secondary procedures to deal with partial loss and cosmetic concerns is common,\textsuperscript{185,186} but all reports note good return of hair growth in the surviving segments of scalp.

**Lip and Nose Replantation**

Traumatic amputation of the lips, nose, or both, remains an unusual occurrence. The largest reported series (from 12 institutions) contains only 13 patients who required lip replantation.\textsuperscript{158} Nasal amputation amenable to replantation has been reported only a few times (one patient had both the lip and nose amputated).\textsuperscript{153–156,181,187} These injuries occur most commonly due to animal bites (primarily dogs) with a lesser number from human bites. Arterial anastomosis in the amputated lip is reasonably straightforward by means of the labial artery.\textsuperscript{158,188,189} As with ear replantation, the primary problem with lip replantation is venous drainage, which is usually addressed with anticoagulation and leeching. Most patients will require transfusion with this approach, which averages approximately 6 units.\textsuperscript{158} Most reported cases have been successful, with loss usually caused by inadequate venous drainage.
Penis Replantation

Amputation of the penis is an uncommon injury and is frequently the result of self-mutilation in patients with psychiatric disorders. The external genitalia can also be avulsed in machinery. Replantation is fairly straightforward, by means of anastomosis of the dorsal and/or deep arteries and dorsal veins. Venous outflow problems have not been reported as with tissues of the head and neck. The reported cases have been universally successful, but failures undoubtedly occur. The author is aware of one case of failure due to the urethral injury and fistula and stricture have been reported. As with small parts of the head and neck, penile replantation offers a result far superior to any available reconstruction.

William C. Pederson, M.D.
The Hand Center of San Antonio
9150 Huebner Road, #290
San Antonio, Texas 78240
micro1@ix.netcom.com

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Self-Assessment Examination follows on page 842.
1. THE FOLLOWING PATIENTS PRESENT WITH AN AMPUTATION. THE MOST APPROPRIATE FOR CONSIDERATION FOR REPLANTATION WOULD BE:
   A) A 63-year-old diabetic suffering a crushing amputation of the index finger
   B) A 5-year-old boy with a sharp amputation of the little finger
   C) A 35-year-old woman with a knee-level amputation of the leg
   D) A 24-year-old man with an amputation of three fingers through the nail bed
   E) A 73-year-old man with an amputation of the arm through the mid-humerus

2. IN COUNSELING A PATIENT REGARDING COLD INTOLERANCE AFTER REPLANTATION OF TWO DIGITS, THE PATIENT SHOULD BE TOLD THAT:
   A) Cold intolerance will quickly go away
   B) Cold intolerance will gradually worsen with time
   C) Cold intolerance will disappear after 2 years
   D) Cold intolerance will diminish for up to 2 years, but may persist
   E) Cold intolerance will not be a problem

3. THE BEST MANAGEMENT FOR A TYPE III RING AVULSION INJURY IS:
   A) Replantation of the degloved skin
   B) Revision of the amputation at the level of adequate soft-tissue coverage
   C) Covering the exposed bony skeleton with a vascularized flap
   D) Ray amputation of the involved digit
   E) Immediate toe wrap-around free flap

4. APPROPRIATE ANTIBIOTIC PROPHYLAXIS AGAINST *Aeromonas hydrophila* INFECTION IS:
   A) Penicillin
   B) A third-generation cephalosporin
   C) Cefazolin
   D) Clindamycin
   E) Erythromycin

5. THE MOST COMMON COMPLICATION OF MAJOR LIMB REPLANTATION IS:
   A) Bleeding
   B) Bony nonunion
   C) Infection
   D) Adult respiratory distress syndrome
   E) Vascular thrombosis

To complete the examination for CME credit, turn to page 905 for instructions and the response form.