Advances of Plastic & Reconstructive Surgery

Chapter 6

Replantation

Eliseo Sara[1]; Mansour Ahmed M[1]*; Miller Nathan F[1]; Mahajan Arnav, BS[2]; Ranganath Bharat[2]; Miles Marshall[1]; Wojcik Randolph[1]; Murphy Robert X[1]; Wallace Sean J[2]

[1]Division of Plastic and Reconstructive Surgery, Lehigh Valley Health Network, 1250 South Cedar Crest Boulevard, Allentown, PA 18103, USA.

[2]George Washington University Plastic Surgery; Division of Plastic & Reconstructive Surgery, The Medical Faculty Associates, 2300 M Street NW 6th Floor Washington DC 20037.

[*]**Correspondence to: Mansour Ahmed M,** Division of Plastic and Reconstructive Surgery, Lehigh Valley Health Network, 1250 South Cedar Crest Boulevard, Allentown, PA 18103, USA.

Email: Ahmed.Mansour@lvhn.org

1. Introduction

Replantation is defined as the reattachment of body parts with restoration of function and sensation. In contrast to revascularization, which is the restoration of blood flow to a devascularized or partially amputated part, replantation is only considered when the amputated part is completely severed and separate from the body and all tissues need to be reattached. Simply repairing circulation to an amputated part that will not provide useful activity does not define success and should be avoided [1]. Replantation surgery has previously been performed in fingers, hands, forearms, feet, ears, lips, tongues, scalps, faces, penises, with finger and upper extremity replantations being the most common.

History

Reattachment of digits dates to the 1800s when William Balfour published the first medical report in the Edinburgh Medical Journal. He wrote of the first digital reattachment when he repaired his son's index, middle, and long fingers. However, these replantations were performed without vascular anastomosis [2]. As such, Douglas and Foster later postulated that the fingers survived as composite grafts [3].

Between the late nineteenth and early twentieth centuries, experimental work in replantation and vascular anastomosis techniques were being pioneered simultaneously by Halsted, Hopfner, Abbe, Sabatini, and Carrel, laying the groundwork for free flaps and replantation of limbs. Sabatini is credited as the first surgeon to have performed a vascular anatomy-based tissue relocation and he reported the labial artery flap in 1838 [4]. While Abbe was the first to experiment with a partially amputated canine limb, with all tissues severed except the brachial artery and vein, Alex Carrel performed the first extremity replantation in 1906 on a completely amputated canine hind limb. Carrel then went on to win a Nobel prize in 1912 for his pioneering work on vascular anastomoses and organ transplantation [2, 4]. Sixty years after the first experimental replantation, the first successful reattachment of a human limb was accomplished by Malt and McKhann [4].

Since then, clinical replantation and reconstructive surgical techniques became more established. Advances in microsurgery followed, and during the 1970s and 1980s, replantation centers around the world were reporting replantation success rates higher than 90% in some patients [2]. Refinement in replantation is still ongoing and most current literature focuses on long-term functional outcomes [2].

Initial Considerations

Some of the initial considerations can differ based on level of amputation, technical aspects, and general approach to replantation. Technique and approach vary by surgeon – one team vs. two team approaches, sequence of structure repair, and osteosynthesis techniques are all dependent on surgeon preference and comfort with the procedure.

Indications and Contraindications

Shared decision making between the patient and physician plays a crucial role in determining if replantation is the best treatment option. Cause of injury and classification of the amputation varies, but the indications for replantation have broadened as surgeons have gained experience in salvage of more complex injuries [1].

Injuries can arise from multiple etiologies including, machine injuries, assault, and even self-mutilation. Out of these, traumatic injuries are the most common cause of amputation, especially of the hands, fingers, and upper extremities [5]. One study of epidemiologic analysis of finger amputations over 20 years found that the highest incidence rates to be in children less than five years old and in adults over the age of 65 years [5,6]. Gender discrepancies exist with digital amputations with approximately 75% of amputations being in men [7]. Industrial occupational hand and finger injuries commonly lead to amputations, as they are most caused by metal items and hand tools with sharp blades and powered machinery [5,7].

While the indications and contraindications for replantation are not absolute, the following are considered general guidelines when deciding whether to replant the limb [1]:

Indications

- Amputations at any level in children
- Multiple finger/hand amputations
- Amputations at the level of the palm wrist or forearm
- Transmetacarpal and partial hand amputations
- Single finger amputations distal to the flexor digitorum superficialis insertion in adults
- Thumb amputations at any level
- Ring avulsion injuries

Contraindications

- Severe crush injuries of avulsion amputations, as there is often significant vessel damage
- Single digit amputations proximal to the flexor digitorum superficialis insertion in adults
- Prolonged ischemia
- Severe contamination
- Multiple segmental injuries in the amputated part
- Concomitate life threatening injuries
- Prior history of surgery or trauma to the amputated part
- Medical co-morbidities and severe systemic illness that affect peri-operative care
- Refusal to accept blood transfusions or blood products for major amputations

Initial Evaluation and Management

Initial evaluation of a potential replantation includes extensive examination to rule out associated injuries, which is especially important in cases where attention may be focused solely on the amputation, like in major replants. When the patients arrive to the emergency room or trauma bay, there is a risk of potentially missing severe injuries due to focus on the amputated limb. Resuscitation and stabilization of the patient should take precedence over treatment of the amputated limb, always beginning with the Advanced Trauma Life Support (ATLS) protocol.

Active bleeding is often found on initial evaluation of the patient, especially in incomplete amputations with partial vessel lacerations. Pressure dressings and temporary use of tourniquets are preferred over blind attempts of clamping or ligating, which may result in further injury to vessels and nerves [8]. Assure that the amputated segment was brought with the patient and that it was stored and imaged properly. The residual limb should be irrigated with sterile saline or lactated Ringer's solution, and then dressed in nonadherent petroleum gauze and covered with a dry, sterile compression bandage and placed into a sterile container that is then placed into a bath of ice and water [8]. The limb should never be directly placed on ice or submerged, as it can macerate the limb. Incompletely amputated limbs are more difficult to manage, as rotation of the part can cause kinking or tourniqueting of attached structures. The limb should be realigned and splinted gently with minimal manipulation to prevent further damage [8].

After initial stabilization, imaging should be obtained of the stump and amputated segments to evaluate the extent of the injury. The length of ischemia time should also be determined. Tolerability of the amputated segment to prolonged ischemia depends on the presence and amount of muscle mass. Limb amputations that are more proximal with larger muscle mass, like the forearm and arm, only tolerate warm ischemia times of 6 and 12 hours, respectively, and are at higher risk of developing reperfusion syndrome and subsequent limb loss [9, 10]. Hands and digits have less muscle mass and tolerate longer warm and cold ischemia times of 12 and 24 hours, respectively [10].

Tetanus prophylaxis is given to patients with unknown immunization status or if last vaccination was given over five years prior. Prophylactic antibiotics with first generation cephalosporins are indicated in amputation injuries directed toward the most likely organism, *Staphylococcus aureus*. An aminoglycoside and/or third-generation cephalosporin may be required in amputations associated with more extensive contamination [8].

When obtaining a history from the patient, a discussion of willingness to comply with rehabilitation protocols, time off work, and subsequent operations is particularly important. Additionally, smoking status, preexisting illnesses, hand dominance, previous surgeries, and mechanism of injury are all important to know when determining candidacy for replantation surgery. Physical exam should include all key components of a hand and upper extremity exam focusing on your observations, as well as vascular, sensory, and motor exams.

Classification

Amputations are classified based on completeness of the amputation, the anatomical level of separation, and the mechanism of injury. Description of the amputation based on these three criteria helps in the decision-making process and in determining if the patient should be transferred to a replantation center for repair.

Completeness of the amputation defines whether the repair will utilize a revascularization or replantation approach. Incomplete, or subtotal/near-total amputations often require revascularization rather than true a replantation procedure. A revascularization may appear to be an easier operation, however, in practice it is often more difficult. The presence of intact bone often limits the ability to shorten the bone, and may necessitate vein, nerve, or skin flaps to bridge the defect. An incomplete amputation also makes intraoperative examination more difficult, as it cannot be manipulated as easily to view and isolate neurovascular structures.

Amputations can also be classified based on the anatomical level of separation. Upper extremity amputations are broken up into two broad categories based about the radiocarpal joint. Major amputations of the upper extremity are defined as amputations proximal to the radiocarpal joint, while minor amputations of the upper extremity are defined as amputations distal to the radiocarpal joint [11]. Systemic complications like myoglobinuria and renal failure are directly related to muscle mass and ischemia time, as previously mentioned, and major limb amputations are unsurprisingly at highest risk for these complications. Therefore, the success of a major limb replantation depends on establishing circulation early on.

Digital amputations are further classified based on anatomic level and zone of injury. Several classification systems exist, such as Hirase, Allen, Ishikawa, and Tamai classification systems, but the Tamai classification system is most frequently used [5,11]. In his study, Tamai classified digital amputations based on five zones of injury extending from the lunula (most distal portion of zone 1) to the distal half of the corresponding metacarpal (most proximal portion of zone 5) [12]. He describes different anatomical characteristics of each digital zone that influence the technique and outcome of replantation [11,12]. The Allen, Hirase, and Ishikawa classification systems describe fingertip amputations rather than whole digit amputations [13]. Classifications of the systems can be seen in **Figure 1**.

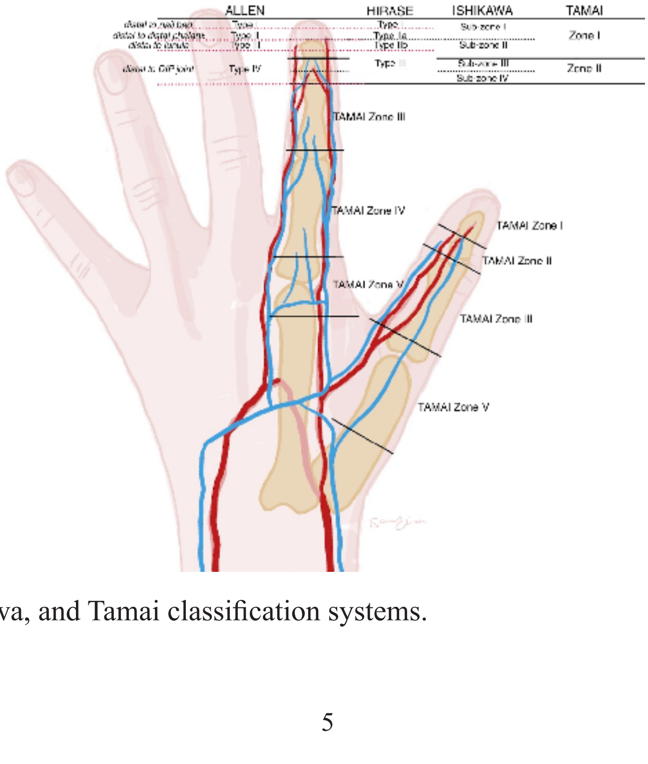

Figure 1: Allen, Hirase, Ishikawa, and Tamai classification systems.

Mechanism of injury is another way for amputations to be classified. Blade injuries, saw injuries, crush injuries, and avulsion injuries are some other names that can be used to describe the severity of the amputation [13,14].

Eaton Hand Coding

Common CPT codes based on level of amputation are listed below: [15]

Replantation

- Replantation, arm (includes surgical neck of humerus through elbow joint); complete amputation [20802]
- Replantation, forearm (includes radius and ulna to radial carpal joint); complete amputation [20805]
- Replantation, hand (includes hand through MCPJs); complete amputation [20808]
- Replantation, digit, excluding thumb (MCPJ to FDP tendon insertion); complete amputation [20816]
- Replantation, digit, excluding thumb (distal to FDP tendon insertion); complete amputation [20822]
- Replantation, thumb (CMC to MPJ); complete amputation [20824]
- Replantation, thumb (MPJ to distal tip); complete amputation [20827]

Revascularization

- Repair blood vessel, direct; hand, finger [35207]

Replantation Center Criteria

Initial evaluation of most digital and hand amputation patients is oftentimes accomplished by non-specialists before referral to hand and microsurgeons [11]. Replantation surgery is a complex procedure that often requires a multidisciplinary approach, and these specialized services are not ones that every hospital or healthcare network can offer. Significant organization, skill, and teamwork is required for successful replantation outcomes.

Replantation centers are held to high standards and must meet certain criteria to qualify. Efficient ground and air transport systems, experienced microsurgical and hand teams, well-prepared emergency rooms, experienced anesthetists and OR microsurgery-experienced staff available 24/7/365, proper instruments, supplies, and microscopes, trained nursing staff for post-op care, and occupational therapists trained in hand therapy are all required to meet replantation center criteria.

Before transport, an attempt should be made to contact the center to determine the appropriateness of the transfer, and to allow preparation for replantation. A detailed history as described above should be provided to the replant team over the phone, and digital photographs of the injured part can help tremendously. All patients deserve an evaluation from an experienced microsurgeon and should be referred to appropriate centers where they can be guided towards decisions that serve their best interests.

Operative Management and Technique

Upon arrival to the replantation center, the amputated part is promptly brought to the operating room to be examined under an operating microscope by one team or physician while the patient is being evaluated for possible replantation by another [2,11]. Like most complicated reconstructive and microsurgical procedures, replantation surgery can take an extended period, so a two-team approach is preferred as it helps to decrease operative times, increase efficiency, and decrease surgeon fatigue [11,16]. One team prepares the amputated limb as necessary, preserving the part at 4°C until the time of revascularization [2]. Intraoperatively, one team will continue to work on the amputated limb while the other team works on the stump simultaneously.

Replantation surgery can be performed either under regional anesthesia alone or in combination with general anesthesia. Regional anesthesia results in vasodilation and facilitates vascular anastomosis while providing the benefit of a sympathetic blockade, which can also be maintained in the postoperative period [2,11].

Replantation Sequence

Variability in surgical methods and techniques exists among different surgeons. While the exact order of repair depends on surgeon preference and level of amputation, most replantations are performed by first repairing deeper structures that require gross manipulation (bones and tendons) followed by superficial structures that necessitate use of an operating microscope (nerves and vessels). Below is an example of a commonly used replantation sequence:

- Evaluation of structures
- Prepare stump and debride the wound
- Identify and tag arteries, veins, nerves, tendons
- Stabilize and repair bones
- Repair extensor tendons/muscles

- Repair flexor tendons/muscles
- Anastomose arteries
- Anastomose veins
- Coapt nerves
- Soft tissue coverage

Intraoperative Evaluation, Preparation, and Identification of Structures

Amputated part: The amputated part is cleaned with routine bacteriocidal solution such as betadine and placed on a small operating table. Debridement and dissection of the limb is done to identify, isolate, and tag neurovascular structures that need repair. Exploration and evaluation of the limb to decide if nerve and/or vessel grafting may be necessary may also be done at this time or intra-operatively. Bone shortening is also necessary in many situations as it allows for primary repair of vessels and nerves while preventing additional need for soft-tissue coverage. Bone shortening is preferred in the amputated part over the stump to maintain a greater stump length to allow for facilitation of a prosthesis in the event the replant fails [17]. Under no circumstances should the tissue or devascularized limb be discarded without first consulting with the replant surgeon- amputated parts that are deemed unsuitable for replantation may still be used for nerve, skin, arterial, or bone grafting [2,8,18].

Vessels: When evaluating vessels for feasibility for repair, it's important to know what is normal versus what is abnormal. Normal vessels should be pearly, grey, and smooth with no petechiae. A corkscrew appearance of the arteries is known as a "ribbon sign" and suggests avulsion of the vessel. Severe avulsion injury can also result in bruising of the skin along the course of the digit, known as "red line sign". Stretched and traumatized vessels may also be speckled due to rupture of the vasa vasorum, known as "measles sign". The "cobweb sign" is indicative of intraluminal clot formation. When any of these signs are present, the replant may not be successful, and vessels should be trimmed until normal appearing vessel is seen.

Nerves: Evaluation of nerves involves meticulously bread loafing the nerve to pinpoint bleeding and healthy-appearing fascicles. "Snail eyes" or "yeux d-escargot" appearance of nerve endings are a sign of regrowth and regeneration of axons [1].

Figure 2: A. "ribbon sign"; B. "red line sign"; C. "measles sign"; D. "cobweb sign"; E. "snail eyes" or "yeux d-escargot"

Osteosynthesis

Bone fixation, otherwise known as osteosynthesis, is performed first. Bone should be debrided back to healthy-appearing bone. Bone shortening can decreased tension on vessel and nerve anastomoses, but should be no more than 5-10mm on a digit and 4-6cm on the forearm.n K-wires are commonly used to span the site where the bone was cut to hold it in rigid fixation, but intraosseous wires are used as well. Both internal and external fixation methods are used. External fixation is typically used in cases of significant bone destruction where contracture of soft tissues can be avoided by external fixation. Internal plate fixation allows for more rigid fixation and easier early mobility, but typically increase operating time as there is a requirement for increased bone stripping to expose the bone for plating [1,13]. However, plate fixation can lead to imperfect alignment if excessive bone shortening was performed.

Tendon and Muscle Repair

After osteosynthesis is tendon repair. Any excess tendon from bone shortening is excised. The decision on whether to repair the extensor or flexor tendon first is dependent on surgeon's preference. The tendons are meticulously repaired with non-absorbable sutures to allow for early mobilization and decreased adhesions. Flexor tendons undergo a lot of stress and should be repaired with a combination of at least a four-strand core nonabsorbable suture. Epitendinous sutures on the flexor tenons can add increased strength and improve tendon gliding [19]. However, some surgeons expidite this step and only repair the profundus tendon to decrease tendon adhesions between the repaired profundus and superficialis tendons. Extensor tendons are under less stress and are repaired using figure-of-eight horizontal mattress, or locked running sutures [11].

Vessel Preparation and Anastomosis

Preparation of the vessels includes trimming back the vessel end to a healthy-appearing location and dissecting the vessel end free of adventitia that may otherwise obstruct the anastomosis.

There is controversy whether arterial or venous repair should be done first. Establishing venous outflow first can minimize blood loss and completes one of the most difficult aspects of the replantation early on. However, early arterial repair can re-establish perfusion of the tissues and eliminate metabolite breakdown products that are produced from tissue ischemia [2]. This is preferable in distal replantations where the arterial inflow helps with identifying veins and in major limb replantations to decrease ischemia time. However, the field is bloody, and dissection is difficult. Reinflating the tourniquet at this stage may increase the risk of arterial thrombosis due to stasis of blood within the anastomosis.

While some surgeons recommend repairing all visible arteries, one digital artery repair is enough for a digital replantation and may optimize time in the operating time. In contrast, if possible, it is recommended to perform multiple venous anastomoses to improve outflow and increase chances of replant survival. Arterial anastomoses are hand-sewn, and venous anastomoses can either be hand sewn or coupled. Submillimeter veins are too small to be coupled, and must be hand sewn if. Despite bone shortening allowing for decreased tension on vessel anastomoses, vein grafts are usually required for bypassing vasospastic or damaged vasculature [11]. Appropriately sized donor grafts can be found in the volar forearm, dorsal foot, or from other spare parts. Alternatively, cross anastomoses between radial digital to ulnar digital arteries, transposition of a digital artery from adjacent digits, or an arterialized venous flow-through flap can be used, as well.

Heparinized saline is used for flushing vessels and for irrigating the surgical field. Irrigation of heparinized saline facilitates vascular patency and easier uptake of sutures [2, 13]. Solutions are mixed anywhere from 10 to 100 units per milliliter in either normal saline or lactated Ringer's solution. Topical 2% lidocaine and papaverine can be used to irrigate vessels and alleviate vasospasm, and multiple studies report improved potency of microvascular anastomoses with usage [20,21].

A strip test can be performed after all anastomoses are complete to assure flow. This can be performed by gently grasping the vessel distal to the anastomosis with two forceps and then milking the blood distally, collapsing the vessel between the forceps. If patent, blood will fill the collapsed portion of the vessel when grasp is released. Micro hemoclips can be used to assure hemostasis.

Nerve Preparation and Coaptation

Some surgeons will perform the nerve coaptation prior to vessel repair, as long as it does not interfere with the arterial repair, as it is far more difficult to perform in the blood-filled field left after tourniquet is deflated [1]. As previously mentioned, the nerve is trimmed back until healthy-appearing and undamaged nerve is visualized. Nerves are frequently repaired using two or three nylon epineural sutures, and while primary repair is always preferred, autologous nerve grafting or a nerve pedicle flap may be required in cases with gross nerve deficiency [2,11]. In digital nerve reconstruction, nerve grafts may be harvested from the forearm (medial antebrachial cutaneous nerve or posterior interosseous nerves are ideal) or from another digit that is not suitable for replantation [2,11]. A graft harvested from the distal end of the posterior interosseous nerve is useful in bridging short gaps, whereas a graft from the medial antebrachial cutaneous nerve is more suitable for longer defects. In multiple digital amputations, nerve grafts are harvested from the discarded digits or cadaveric nerve graft is considered [20].

Soft Tissue Coverage

Meticulous hemostasis is assured, and the skin flaps are loosely approximated with a few interrupted sutures. Exposed tendons are covered by transposing local skin flaps. Other residual areas may be left open to heal secondarily or covered with small split-thickness skin grafts.

Post-operative Recommendations and Management

Risk of post-operative thrombosis is in the first 72 hours after surgery, and patients are kept NPO for the first 24 hours in case they need to be taken back to the operating room emergently. Arterial thrombi usually result from platelet aggregation and present on post operative day 1, whereas venous thrombi result from fibrin clotting and usually present by post-operative day 2. Postoperative care is directed towards preventing such external factors from occurring. Dextran 40 is generally provided to protect vessel patency for the 5 days following surgery, during which the blood vessel lumen is at an increased risk of becoming occluded [1]. Aspirin is also typically prescribed the day of surgery and continued for 2-4 weeks post-operatively the room is kept warm, and the patient is kept well hydrated. The replanted part is kept elevated above the level of the heart. Appropriate analgesics are used to control pain and anxiety, as this can lead to an adrenergic response and vasoconstriction. As with all microsurgical procedures, smoking is prohibited in order to reduce risk of hypoxia, thrombosis, and decreased perfusion of the replant. Minimal bandaging is preferred to evaluate appropriate color, turgor, and capillary refill. Adjuncts to clinical judgement include doppler and pulse-oximetry [2].

Hand and arm physiotherapy involving sensory re-education and joint mobilization is crucial in regaining function of the replanted limb [13]. Physical therapy can be initiated about a week after surgery, and extent depends on the level of the replant and the stability of skeletal fixation. The patient should initially be undergoing physical therapy daily in the outpatient setting, and thereafter on a weekly basis until a plateau is reached, usually around 2-3 months postoperatively. At this point, there is discussion of possible secondary procedures to enhance function, like nerve grafting, intrinsic muscle release, tendon transfers, or tenolysis.

Managing a Failing Replant

Immediate action should be taken if there is suspicion of compromised perfusion. Any dressings or sutures causing constriction are removed, and the patient is brough back to the operating room immediately if perfusion does not improve. On physical examination, replants with arterial insufficiency will appear cool, pale, with no capillary refill, and no bleeding on pinprick. Replants concerning for venous congestion will present with increased turgor, congested, and will produce dark blood on pinprick. Rarely, kinks can occur and give rise to thrombi. These can be resolved by simple manipulation and revision of the anastomosis, ensuring that the vessels are positioned correctly. Interposition vein grafts can be used for the more-common thrombi that developed due to the anastomosis. If venous congestion persists despite a patent venous anastomosis, medical leeches can be used to decompress blood from the tissue until neovascularization occurs. Leeches also secrete hirudin, which is a naturally occurring anticoagulant.

Late complications can arise and are unsurprisingly associated with tendon adhesions and joint contractures. While replantation surgeries are becoming increasingly successful, it is important to be mindful that secondary procedures are almost always required.

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