REPLANTATION OF THE EXTREMITIES PROXIMAL TO THE HAND

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The first successful replantation of an amputated human extremity was performed in 1962; Malt has recently described the long-term result of the first patient, who did extraordinarily well both physically and psychologically and works full-time as a truck driver moving heavy carcasses of beef. The procedure attracted the interest of the medical profession and the public. Subsequent improvement in instrumentation and technique has allowed successful replantation at any level of the upper extremity. The relative newness of the procedure, the importance of patient selection, and the necessity for continued critical evaluation of results justify consideration of limb replantation as an entity. The even more recent and rapid development of digital replantation is discussed in a subsequent chapter.

HISTORICAL ASPECTS

Man's long-standing interest in restoration or replacement of severed human parts is amply demonstrated in legend, illustrations, and reports of crude surgical maneuvers. Modern surgical investigation directly related to replantation began in 1887, when Halsted divided and repaired all structures of the hind limb of dogs except the femoral artery and vein. These experiments were stimulated by Dr. Halsted's interest in postmastectomy edema and were not performed until 1922. In 1903, Hopfner described experiments in which dogs' limbs were amputated and replanted using a nonsuture method of vascular anastomosis, with maintenance of viability up to 11 days in one animal. Shortly thereafter, Carrel and Guthrie were also able to replant an extremity in a dog with short-term survival. In 1908, Carrel described a dog leg homograft that survived for 22 days. Very few experimental attempts at replantation were recorded between 1908 and the report of Lachpinsky in 1960. Subsequently, several investigators have described experimental replantation and have added a substantial amount of information regarding the technique and physiologic effects of extremity replantation.

In 1944, a protocol for replantation of amputated human extremities was formulated and published. In 1962, a 12-year-old boy presented at the Massachusetts General Hospital shortly after sustaining a traumatic amputation of the right arm below the shoulder. Dr. Ronald Malt, then a resident in surgery, made the decision to attempt replantation, assembled several surgical colleagues, and promptly performed the first successful limb replantation. The efforts of a number of laboratory workers, and particularly the careful, objective report of successful limb replantation in two patients by Malt and McKhann, stimulated worldwide interest in replantation.

The first successful replantation at a digital level was performed by Komatsu and Tamai on July 7, 1965. The laboratory development of techniques and instrumentation for microsurgical surgery has stimulated increasing interest and experience in replantation.

CLINICAL EXPERIENCE WITH REPLANTATION

Replantation experience, including all levels of amputation, numbers several hundred patients. Operations have been carried out in many geographic areas, and it is of interest that the largest single institutional series are from China and Australia. It is likely that the total number of replantation procedures performed is considerably greater than that reported. Variations in the completeness and timing of scientific reporting allow only general conclusions to be drawn from the recorded clinical experience. Recent reports on extremity replantation from China indicate a very large experience. A series of 438 patients was reported with a survival rate of 83 percent for replaced limbs and 57 percent for replanted digits. The survival rate in recent patients in whom microsurgical techniques were
primary closure or in which the time interval militates against primary closure should certainly not be considered acceptable for attempted replantation.

**Results**

The success rate in achieving extremity viability is approximately 75 per cent for major upper extremity replantations. Because it seems likely that the most successful cases have been reported, these may be optimistic figures. Early failure has usually been described as due to circulatory inadequacy or infection. Late failure has virtually always been due to faulty innervation.

With current techniques, the end result after extremity replantation is never perfect. For practical purposes, the end result is dependent upon the extent of nerve regeneration. Experience with extremity replantation confirms the long-accepted observation that peripheral nerve regeneration is more complete (1) in young persons, (2) in sharply incised wounds, and (3) in more distal wounds. The collected replant material does not permit correlation of either technique or timing of nerve repair with the ultimate degree of regeneration. Many surgeons now feel that primary repair of nerve trunks by epineural or fascicular suture is highly desirable when possible. Early secondary repair has been successfully performed in many instances. It is also not possible to accurately define functional success in extremity replantation. In general, the procedure is considered successful if the patient and the evaluating physician feel that the extremity function is preferable to that of currently available prosthesis (Fig. 1). Using this criterion, the outcome of replantation operations has been termed successful in a high percentage of patients reported.

**Incomplete Traumatic Amputation**

It is obvious that the incompletely severed extremity offers virtually the same surgical challenge as com-
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al militates to be considered.

viability is beyond question, the most severe may be delayed infection, to faulty

After extremity pursuit of the primary sustainability that permits (1) in s, and (3) in at material technique or the degree of at primary vascular support, a many indirectly defined. In general if the patient exogenously, the seen termed reported.

ed extremity usage as complete amputation. Reviews of replantation have customarily not included cases of incomplete amputation because the presence of a viable tissue pedicle introduces so many variables into the assessment of results that even general conclusions become impossible. It is recognized, however, that one of the principal benefits of the recent interest in extremity replantation is a trend to more careful assessment of the badly injured extremity and the consequent salvage of extremities that might formerly have been amputated.

Summary

Experience with upper extremity replantation is encouraging. Better understanding of the basic processes involved and particularly of peripheral nerve regeneration should lead to improved results.

Basic Considerations in Replantation

Extremity replantation involves many basic considerations. Most obvious is the necessity for detailed anatomic knowledge. Surgical restoration of an amputated extremity requires knowledge of wound healing, the factors that influence healing, and the time required for the healing process. Incomplete understanding of the healing of peripheral nerve is the greatest single deterrent to success in major limb replantation. The observation that infection is a major cause of early failure after limb replantation emphasizes the need for knowledge of surgical microbiology and for an understanding of the methods of minimizing, detecting, and treating bacterial infection. A basic problem shared with other vascular procedures but uniquely severe in replantation is the phenomenon of ischemia and restoration of blood flow. Several important questions regarding ischemia and restoration of flow may be posed. What is the maximal period of ischemia that will allow restoration of function by re-establishing circulation? What factors modify the period of permissible ischemia and, particularly, how can this period be prolonged? What problems are associated with restoration of blood flow and how can these be minimized or prevented?

Ischemia

When blood flow to an extremity is completely interrupted (as in traumatic amputation), the available oxygen is quickly exhausted and anaerobic metabolism begins. Ultimately, an irreversible state is reached when restoration of blood flow will no longer result in recovery. The length of time between the onset of ischemia and the state of irreversibility varies widely from one tissue to another. Skeletal muscle is the tissue in an extremity that is most sensitive to ischemia, followed by skin, fat, nerves, and bone. In experimental preparations, the ability of skeletal muscle to contract after electrical stimulation diminishes after 2 hours of ischemia and is totally lost after 4 hours. Few gross or microscopic changes can be detected in ischemic muscle until 4 to 6 hours after ischemia is produced, although depletion of glycogen and ATP has been described. Most studies of the maximal period of tolerance for ischemia have involved re-establishing flow after varying periods of ischemia in a variety of experimental preparations and studying the morphologic, physiologic, or biochemical changes that occur. When flow is restored in experimental preparations, necrosis of some skeletal muscle cells follows an ischemic period of about 2 hours’ duration, and necrosis is very extensive after an ischemic period of 8 hours. There is some species variation in the resistance of muscle to ischemia, and presumably this is true of other tissues. In the rat, the permissible period of skin ischemia is about 8 hours. It is generally stated that fat, nerve, and bone are more resistant to ischemia, but precise experimental definition is lacking.

Basic studies of the effect of ischemia on skeletal muscle and skin, briefly cited in the preceding paragraph, suggest that an extremity replanted with adequate restoration of circulation after 6 to 8 hours should survive with good recovery of skeletal muscle contractility. This has been confirmed by limb re plantation experiments in dogs.

For obvious reasons, extension of the tolerable period of limb ischemia is desirable in clinical replantation. The oldest and perhaps most widely used agent to accomplish this is hypothermia. Presumably, hypothermia slows the metabolic processes that lead to an irreversible state. The optimal degree of hypothermia and the exact period of protection that might be offered by hypothermia are not precisely defined. Lachnichsky has reported survival of a replanted, cooled dog leg after 25 hours. A report from China mentions 21 patients undergoing extremity replantation more than 10 hours after amputation, with survival of 14 limbs. It seems significant that cooling during the period of ischemia has been shown to minimize some of the events, particularly edema, that follow restoration of circulation.

Clearing the vasculature of the amputated extremity by perfusion should theoretically prevent the intravascular coagulation of blood and might remove some of the metabolic products of anaerobic metabolism. Such clearing has been shown to be useful in prolonging the life of experimental animals after replantation. The efficacy of several perfusates in clearing the microcirculation has been studied, and the most effective was found to be saline with heparin. Prolonged perfusion using nonoxygenated solutions has no rationale.

Restoration of Circulation

When blood flow is re-established to an ischemic limb, femoral arterial flow rapidly rises to a level exceeding the preamputation flow in the experimental animal. In addition, there is a marked increase in bleeding from the distal muscle ends and a visible reddening of the skin, which has been described as reactive hyperemia. An increase in limb weight occurs rapidly for approximately 2 hours and then increases very slowly for about a week, at which time the edema begins to subside.

Studies of the microcirculation of both skin and muscle show that after ischemia of more than a few minutes’ duration the restoration of flow in major vessels is not followed by uniform flow in the microcirculation. Rather, the return of flow is patchy, with

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some areas filling well and others not at all. The role of lymphatic interruption in the formation of edema is not clear, but there is some evidence that lymph channel reconstruction in the experimental animal reduces the extent of edema.21

The principal recognized systemic effect of restoration of blood flow to a replanted extremity is the frequent development of shock. The appearance of shock after replantation is not consistent, but it has been described both clinically22 and experimentally.21 This shock has been extensively investigated, and at least three explanations for its appearance have been suggested. Most evidence suggests that the shock is due to blood and fluid loss into the replanted extremity.9, 28 Fluid loss into a traumatized extremity was carefully studied by Blalock in classic studies that showed that traumatic shock was not due to a tissue-elaborated toxin.2 The same conclusion with regard to tourniquet shock26 and reanulation shock9, 28 was reached after experiments by others. Since shock is not universally encountered after experimental reanulation, it seems probable that the original condition of the animal, the blood loss during the amputation, the amount of fluid administration during the procedure, types of anesthesia, and perhaps other factors have served to confuse the experimental results. The concept that a vasodepressor toxic substance is elaborated in ischemic tissue and causes shock on restoration of circulation has had proponents since the work of Cannon.4 The question is not whether such a substance might be elaborated after prolonged ischemia26 but whether the effect is clinically significant under the conditions in which reanulation might be attempted. Recent experiments again indicate that it is unlikely that a tissue toxin of significance is elaborated during periods of ischemia of up to 8 hours.26 Mehl has suggested that shock in the post-reanulation period is due to fall in pH, and improved survival using an amine buffer in his experiments was impressive.26 Certainly this work demonstrates the importance of control of pH, whether it is the primary cause of shock or secondary to it.

10 hours, although this is not an absolute figure. If the extremity has been promptly cooled and the circulation can be cleared during the first 8 hours, the time interval may be up to 20 hours. Finally, the impact of reanulation, the expectation of multiple operations, and the necessity for at least 2 years of rehabilitative therapy should be considered in each patient.

Lower extremity reanulation is indicated only in exceptional circumstances, such as loss or threatened loss of the other leg. The principal reason for this is that the function of the lower leg is relatively well accomplished by available prostheses. Also of importance is the fact that a shortened, anesthetic lower extremity is a constant and significant handicap during the period between reanulation and very unpredictable nerve regeneration. It is obvious that improved methods of managing peripheral nerve injury will alter the indications for attempting to replant lower extremities. Reports of clinical experience with lower extremity reanulation are rare.27, 33

The Reanulation “Team”

All aspects of reanulation are integral to other more common surgical procedures, yet experience indicates that preliminary review of the subject by all personnel to be involved will avoid recurring problems and improve the likelihood of success.19 Laboratory experience with the procedure is strongly recommended. Several surgical skills of high order are required. The amputation wound in both the patient and the extremity must be debrided carefully and adequately. The bone must be shortened and skeletal fixation rapidly achieved by any of several methods. Anastomoses of several vessels must be achieved for initial success. The type of magnification required depends on the level of injury. At least two surgeons of the team should be skilled in the techniques of microvascular surgery. Definitive nerve repair, including grafting, should be performed at the original operation whenever possible. Fascicular repair utilizing the microscope is favored. Multiple tendon repairs and a variety of closure techniques, including the use of flaps and grafts, may be necessary.

The anesthetist should be sensitive to the likelihood of hypovolemia. He should anticipate the rapid, sizable blood loss when the extremity circulation is reestablished. The problem of reanulation shock and acidosis should be recognized and prevented or promptly treated by administration of blood, fluid, and bicarbonate.

Good nursing care, physiotherapy using a variety of modalities, and social service support are critical in the postoperative management and rehabilitation of the patient after extremity reanulation.

Steps in Reanulation

At the site of the accident or as soon as possible, the amputated extremity should be wrapped in plastic and immersed in iced water. Control of bleeding from the amputation wound and careful assessment of the general condition of the patient and of the extremity are preliminary to making a decision to attempt reanulation. Preoperative x-ray examination of the extremity and the wound is performed. In avulsion injuries, x-ray examination of the cervical spine is indicated to rule out evidence of nerve root avulsion. If such evidence is
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If the circulation is not patent, myelography should be performed prior to attempting what might be a hopeless replantation. Extremity cooling should be continued. In the operating room, the major artery of the extremity should be perfused with cool balanced salt solution containing heparin and an antibiotic. An intravenous infusion set is adequate, and the perfusion is discontinued when venous drainage becomes clear. Occasionally, extraction of thrombus material by means of a balloon catheter may be necessary. Both the extremity and the amputation wound are carefully prepared for replantation. In addition to mechanical cleansing of the skin surrounding the wounds, extensive irrigation of the wounds with large volumes of sterile saline is important. Débridement of both wounds is performed. Bone stabilization and fixation are initial steps in replantation (Fig. 2). It is essential to shorten the bone at all levels of amputation to allow approximation of other structures. The type of bone fixation depends upon the degree of comminution of the fracture and the anatomic level. A variety of intramedullary devices and plates have been used successfully, and evidence does not strongly favor one method over another. When bone fixation is complete, reconstruction of the veins is begun. This is a critical technical step in the replantation procedure. As many large veins as possible should be identified and careful anastomoses performed. Gentle dilation of the vein ends and placement of traction stay sutures allow construction of accurate, maximsize, end-to-end anastomoses. Very fine synthetic suture is placed with continuous or interrupted technique. Magnification using loupes or a microscope is very helpful. Following completion of at least two, and preferably several, venous anastomoses, the arterial anastomosis is performed. In amputations distal to the bifurcation of the brachial artery, both the radial and the ulnar arteries should be repaired. Vein grafts from the saphenous system can be used to bridge gaps in either arteries or veins. On release of vascular clamps, hemorrhage from the distal muscle ends should be anticipated. This is apt to be massive, and transfusions will usually be necessary at this time. Establishing hemostasis will involve time, pressure, and patient litigation of multiple bleeding points. At this point, débridement of the amputation wound should be completed, as nonvascularized tissue can be accurately identified for the first time. Thorough débridement is important in preventing infection, and its value cannot be overemphasized.

Management of the divided peripheral nerves remains controversial. Early opinions were generally that secondary definitive nerve suture should be performed. Experience with exceedingly difficult secondary operations in dense scar and the hazard of vascular damage have convinced many surgeons that primary nerve suture should be performed when possible. Very careful fascicular suture using the operating microscope appears to give the best chance for useful regeneration. Repair of the muscles is then performed by means of interrupted sutures in the muscle fascia. Subcutaneous tissue and skin closure is routine. Drainage of the wound is indicated in many instances. If adequate skin coverage is unavailable, grafting may be necessary, and tendon, bone, nerve, and vessels must be covered by flap tissue. Following the completion of the procedure, the arm should be elevated and protected by padded splinting in a position of function.

Postoperative Management

Postoperative care of the replanted extremity involves efforts to maintain circulation, protect the extremity against injury, and preserve functional capacity until nerve regeneration occurs. Anticoagulant therapy, fasciotomy, and methods of minimizing edema should be considered in the early postoperative period. The failure of heparin to improve results in experimental replantation and the complications often associated with effective levels of heparin have led to the recommendation that it not be used routinely after replantation proximal to the hand. Fasciotomy may be critical in maintaining adequate circulation and should be performed freely but probably not routinely. Edema is controlled principally by elevation, gently and carefully applied elastic compression, and careful attention to serum protein level. The formation of edema is rapid in the first few hours after replantation, and care to avoid constricting dressings in this period is important.

The anesthetic arm is protected by padding, frequent position changes, and skin care. Physiotherapy should be employed very early in the postoperative period to preserve range of motion and joint function in the extremity. Muscle stimulation is added when healing of the wounds is well established. The cooperation, advice, and assistance of a physiotherapy unit is invaluable in the management of these patients and probably essential in obtaining a satisfactory functional result.

The risk of infection is minimized by appropriate selection of patients, careful and complete débridement, good surgical technique, and early, adequate...
antibiotic therapy. Antibiotic administration is begun prior to the replantation operation, and high intravenous doses of broad-spectrum antibiotics are continued for several days. Prophylaxis against tetanus should not be forgotten. Life-threatening infection is an indication for amputation.

Hypovolemia with its attendant cardiovascular and renal problems is the principal threat to the patient in the early postoperative period. Blood replacement prior to and during the replantation procedure should be as complete as possible, and further blood and fluid administration may be required as fluid is sequestered in the extremity in the postoperative period. Careful attention to blood pH, serum electrolytes, and urine output should allow prompt correction of abnormalities before major damage occurs.

The postoperative replantation patient requires far more than the usual psychologic support from the managing team. The attempt to save an extremity will involve a long rehabilitation period, several subsequent operations, and a lengthy period of doubt about the extent of functional recovery. The managing physician and the many ancillary personnel involved in such procedures must realize the importance of establishing good rapport and maintaining support during this long period of treatment.

During the long period of convalescence following extremity replantation, frequent review of the course, problems, and outlook by all participating personnel is important. The best interests of the patient are served by appropriate timing of subsequent procedures, recognition of problems, and prompt recognition of failure if it should occur. The difficult decision to amputate a replanted extremity is often made more easily and promptly by a multidisciplinary review of the patient's progress.

SELECTED REFERENCES


The authors describe replantation of severed limbs and digits in 426 patients during a 14-year experience at the Shanghai Sixth People's Hospital. The survival rate for replanted limbs was 89 per cent and for replanted digits 77 per cent. Follow-up of 214 patients for more than 1 year showed only 4 per cent with little or no functional recovery, while 34 per cent were able to resume their original work with complete or nearly complete recovery of sensation.


This is the original description of the first successful human replantation experience, which, more than any other factor, stimulated interest in the possibility of extremity salvage by replantation.


This is an extensive review of the pertinent literature concerning the experimental basis for limb replantation, including the authors' investigative experience.

REFERENCES


An excellent review of the subject of both major and digital replantation by an authority.


REPLANTATION OF AMPUTATED DIGITS AND HANDS
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INTRODUCTION AND HISTORY
Digit and hand replantation utilizing microvascular anastomosis of small arteries and veins has become an effective method of reconstructing hands that have sustained complete or incomplete amputations. The first successful replantation of an amputated digit by the microvascular technique was performed by Komatsu and Tamai in Nara, Japan in 1963.

Microvascular surgery implies repair of small blood vessels (3 mm. or less in diameter), using an operating microscope, microsurgical instruments, and ultrafine suture material (usually about 20 μ in diameter). The 10-0 (20 μ) nylon or polypropylene suture, which is swaged on the needle of 50 to 130 μ in diameter, is essential in anastomosing small vessels of a caliber of 1 mm. or less found at the base of an adult digit (Fig. 1).

A total replantation is defined as reattachment of a part that has been completely severed; that is, there is no connection between the amputated part and the patient. Subtotal replantation is the reattachment of a part of which some portion of the soft tissue (such as skin, nerves, or tendon) is still connected. Vascular repair is necessary to prevent necrosis of the partially severed distal limb. Revascularization of a limb is the reconstitution of blood vessels that have been damaged. This may mean repair of either the arteries or the veins or both.

CARE OF THE AMPUTATED PART
Amputated or devascularized tissue will survive for about 6 hours if the part is not cooled. Cooling lessens the metabolic needs of the tissues, and an amputated part may be successfully restored 12 hours after severance if it is cooled. Because the digits essentially have no muscle tissue they may be successfully replanted as long as 24 hours after amputation if they are cooled.

Since most replantations are performed in centers with experienced microvascular teams, the referring physician must be given clear instructions about the preservation of the amputated part and the care of the injured patient. The amputated part should be placed into a plastic bag containing Ringer's lactate or saline solution. The plastic bag is placed on ice. The amputated part must not be allowed to come in direct contact