Microsurgery in trauma: Its evolution and future

by Harold E. Kleinert, MD, FACS, FRACS, Louisville

The most common site of human trauma is the hand. This was recently emphasized during my visit to a large, modern hospital in Ljubljana, Yugoslavia, where 60 percent of 200 trauma patients treated each day suffered from hand injuries. In Louisville, where we have emphasized the importance of primary treatment for hand trauma, more than 85 percent of trauma patients at our primary treating hospital have hand injuries. Since the hand is the body's most frequently injured area, the application of microsurgery as a sophisticated tool in the management of these injuries is an important and timely topic for discussion.

Over the last 20 years, microsurgery has dramatically expanded the horizons of both traumatic and reconstructive surgery. It is a valuable tool for all surgical specialists. Remember, the decisions made and treatment rendered by the first surgeon attending a trauma case play the greatest role in the eventual outcome of that case. For example, if the surgeon decides to amputate an avascular extremity or a portion of it rather than restoring circulation, no amount of reconstructive surgery can reverse that decision.

History

The compound microscope developed by van Leeuwenhoek in 1680 magnified objects 270 times. Joseph Lister added the achromatic lens. Ernest Abbe and the Carl Zeiss Company developed the modern microscope with improved refraction and illumination through the lens. The microscope was not used for clinical surgery until 1921, when Nylen in Sweden used it to dissect the inner ear of a rabbit. Holmgren, for whom Nylen worked, used it to treat human otosclerosis.[2] Otolaryngologists have routinely used the microscope ever since.

Most other surgical specialists were slow to implement its use. The first of the present-day operating room microscopes was developed in 1960 by the Zeiss Instrument Company in collaboration with Julius Jacobson, who used it to repair small vessels. Working with Suarez, Jacobson developed microsurgical instruments, introduced microsurgical techniques, and coined the word microsurgery. In an article published in the *Surgical Forum* in 1960, Jacobson wrote, "It is our belief that the techniques presented will extend vascular surgery to previously inaccessible areas."[3] Thus mircosurgery began its infancy for most surgical specialists in the 1960s.

The principles of modern vascular surgery started with Alexis Carrel in 1901 when he perfected a technique of vessel repair.[4,5,6] In 1903 Hoepfner experimentally replanted dog legs; the dogs survived up to nine days.[7] In 1960 Clifford Snyder reported successful replantation of dog legs.[8] At Louisville in the late 1950s, we restored many avascular upper extremities, and in 1962 restored digital blood flow by anastomosing digital vessels.[9,10] In the early 1960s, unbeknown to one another, both Buncke in California and Chen Chung Wei in Shanghai successfully replanted rabbit ears.[11,12] Thus, the stage was set for the first recorded successful replant of a human arm, which was performed in May 1962 in Boston by Ronald Malt.[13] Thereafter, many successful similar replants were performed, but no successful digital replants were recorded until Komatsu and Tamai replanted the amputated thumb of a Japanese worker in 1965.[14] In 1966 Chen reported several successful cases of digital replantation.[15]

Tissue transplantation

The stages in the history of microsurgery must include tissue transplantation with vascular anastomosis. The advances made in renal transplantation after World War II led to the development of successful models for tissue-transplantation surgery. Joseph Murray in Boston generated much interest in this new field, and Sun Lee in Pittsburgh set up the first transplant laboratory. Thus the concept of tissue transplantation with revascularization was established and the need for small-vessel anastomosis appreciated, but the ability to perform microvascular anastomosis was still more than 15 years away.

In 1966, Buncke and Schulz reported success in transferring, in one stage and as a unit, the great toe to the hands of Rhesus monkeys.[16] John Cob-

*Dr. **Kleinert** is clinical professor of surgery at the University of Louisville School of Medicine, KY, Indiana University, Bloomington, and Purdue University, Lafayette, IN. He is also the national consultant in hand surgery to the Surgeon General, United States Air Force.*

bett of England, who studied with Buncke, clinically transferred a large toe to replace an amputated thumb in 1968.[17] This operation, together with a clinical transfer of vascularized omentum performed by Buncke, opened up the clinical field of free-tissue transfer by microvascular anastomosis.[18] In 1964, Michon and Masse applied microsurgical techniques to peripheral nerve repair.

The impact of microsurgery on the repair and reconstruction of the injured hand was immediate and involved almost all surgical subspecialty fields. Continued interchange of ideas among early microsurgeons such as O'Brien and Taylor in Melbourne, Lendvay and Owen in Sydney, Tamai and Ikuta in Japan, Millesi in Austria, Cobbett in England, and Buncke in this country stimulated the mushrooming field of microsurgery.

In May of 1973, a visit to China by a group of North American surgeons provided a further stimulus to the development of microsurgery in the United States. The Chinese emphasized the importance of replantation, transposition, and free vascular tissue transfer. They taught us to shorten bone to overcome significant soft-tissue defects necessitated by adequate debridement and to permit repair without tension, which is the greatest enemy of all surgeons, especially microvascular surgeons.

William Littler of New York described the use of an island neurovascular pattern flap taken from a finger to reconstruct a thumb, and thus crystalized the idea of axial pattern flaps for hand surgery.[20] The year 1973 saw the vascular pattern groin flap, developed in Scotland by McGregor, used as a free-tissue transfer by microvascular anastomosis in three different countries: Australia, Japan, and China.[21]

The first surgeons to practice microsurgery were largely self-taught, in both the laboratory and clinic. By 1974, several major medical centers had established microsurgical research laboratories to train residents and fellows. Many laboratory directors wisely realized the value of providing microsurgical training to all interested surgical specialists. General, plastic, and orthopaedic surgery specialists in particular quickly seized this opportunity. Microsurgical investigation combined with microanatomical dissection has identified a multitude of donor sites for clinical microneurovascular free-tissue transfer for reconstruction in both emergency and elective surgical patients.

The introduction of improved microscopes, microsurgical instruments, and sutures coincided with clinical advancements. Pioneers in the field, such as Buncke, O'Brien, and Acland, made their sutures and many of their instruments by hand. Suture and instrument companies became interested in this new specialty, and by 1974, sophisticated instruments, needles, and sutures were available for microsurgery. Other manufacturers entered the field, and prices became competitive. Operating microscopes were improved through motorized focusing units, zoom optics, and optical tracks triggered by foot or hand control.

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Major and minor replantation

Within its history of less than two decades, replantation surgery of the limbs has branched into two groups: major and minor limb replantation. Surgeons have learned to deal with the problems of major limb amputation and reattachment and the possibility of subsequent systemic toxemia. Many successful cases of major upper limb and some of lower limb reattachments have been reported. No prosthesis can compare to an extremity with two-thirds of its motor and sensory functions restored. Replantation, to be successful, must function better than any prosthesis and be cosmetically acceptable.

Factors that influence indications for replantation include:

- The patient's age; young patients are more likely to regain nerve function than older patients.
- Warm ischemia that does not exceed six hours (major replantation).
- Cold ischemia that does not exceed 24 hours (major replantation).
- All sharp amputations with minimal tissue destruction.
- Amputations of more than one extremity.
- Amputations of more than one digit and fingertip amputations (Figure 1A and 1B).
- Thumb amputations.

Relative contraindications to replantation include:

- Crushing or avulsion amputations.
- Severe damage to the amputated part.
- Amputations of lower extremities.
- The presence of other life-threatening injuries.
- Elderly patients.
- Pre-existing systemic diseases.
- Heavy contamination.

Relative contraindications, such as avulsion or crushing amputations, are often overlooked especially in young patients.

In most countries of the world, many minor limb replantations have been performed since 1970; minor replantations are defined as distal to the wrist or ankle joint. Especially rewarding to the surgeon are hand and digit replantations.

As young, expert, and proficient microsurgeons with formal microsurgical laboratory training and experience entered the field, smaller and smaller caliber vessels were repaired in order to replant more distal amputations. Replantation is the most suitable method of restoring an amputated fingertip when the indications for replantation are present. Finger motion, sensation, and cosmetic appearance can be restored to near-normal. It is possible to successfully anastomose vessels as small as .3 mm in diameter (Figure 2A and 2B).

Relative contraindications for minor replantation include:

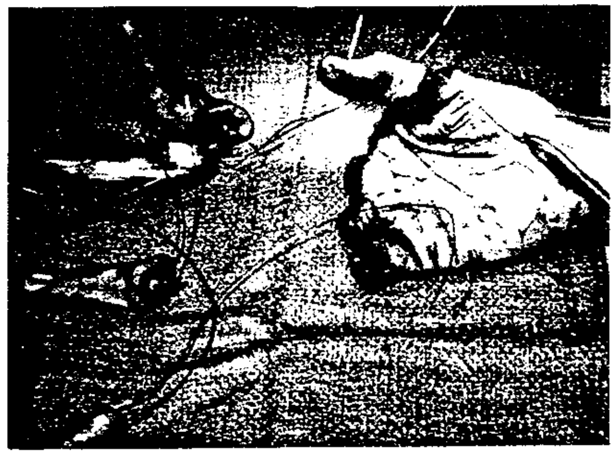

***Figure 1A.** G. F., an 18-year-old male, amputated the thumb and all four fingers of his dominant right hand on a table saw.*

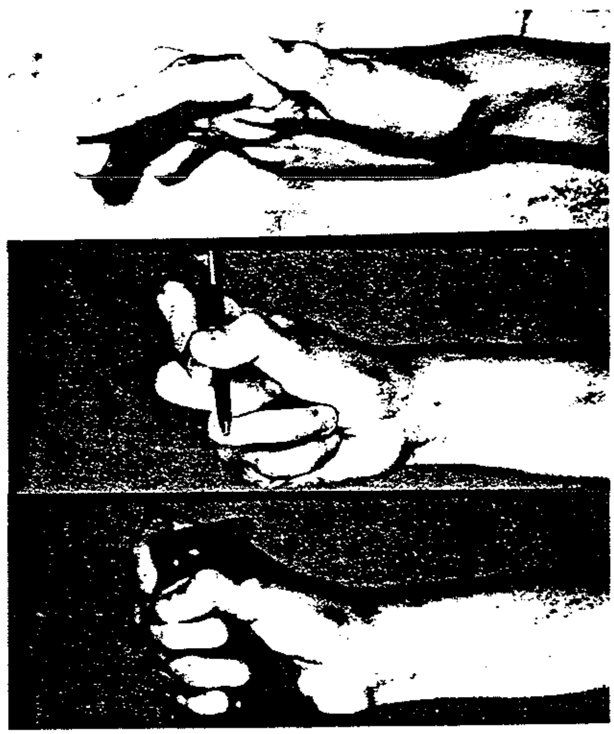

***Figure 1B.** Excellent function 16 months postoperative. (Courtesy G. D. Lister, M.D.)*

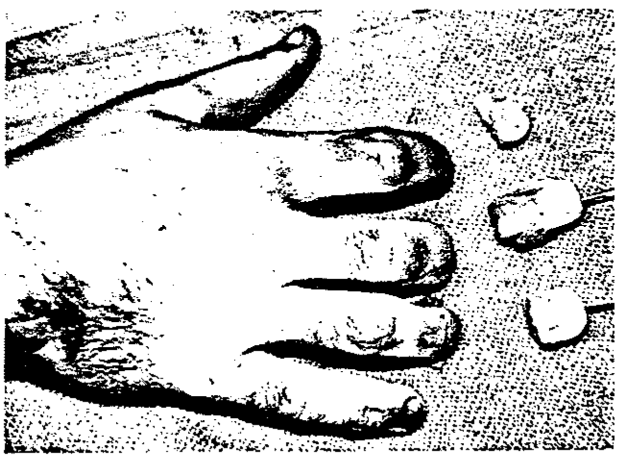

Figure 2A. G. J., a 16-year-old male whose dominant middle finger was sharply amputated at the distal interphalangeal joint level, the index and ring more distally. (From Kleinert, H. E. and Tsai, T. M.: Microvascular repair in replantation. Clin. Orthop. and Related Research, Vol. 133, June 1978.)

Figure 2B. Results six months after replantation.

- Crushing or avulsion injuries.
- Severe damage to distal parts.
- Amputations of border fingers (fingers 2 and 5, except the tips—Figure 3A, 3B and 3C).
- Amputations of a single finger (except the tip).
- The presence of other life-threatening injuries or pre-existing diseases.
- Elderly patients.
- Warm ischemia of more than eight hours; cold ischemia of more than 40 hours.

Cases of multiple-digit amputation with severe destruction of some digits and less damage to others are treated by transposition of parts, i.e., the digits suitable for restoration are reattached in the area of greatest need, such as a finger for a thumb.

Operative techniques

Wound closure and vascular repair tension must be avoided because they lead to both arterial and venous thrombosis. Vein grafts are used in most replants as vascular grafts for both arteries and veins in order to avoid tension. The vein graft for arterial repair is reversed. The chance of thrombosis can be further minimized by attaching the graft proximally and distally to any intimal damage. Twisting or kinking of vessels, grafts, or anastomosis sites must be avoided. Hemostasis of deep collateral circulation, such as in the branches from the deep arch in transmetacarpal amputations, is meticulously accomplished prior to reattachment, or the replant may fail due to complications from hematoma. If at all possible, all structures should be repaired in this order:

- Fix bones with interosseous wires, Kirschner pins, or intramedullary pins or screws, as indicated.
- Repair extensor muscle units.
- Repair flexor muscle units.
- Repair arteries.
- Repair veins.
- Repair nerves.
- Cover loose soft-tissue.

Crushed and devitalized tissue is completely removed. Additional incisions made to expose veins, arteries, tendons, and nerves should be planned so that they can be transposed as Z-flaps to avoid circular, constricting scars. Vein grafts, when necessary,

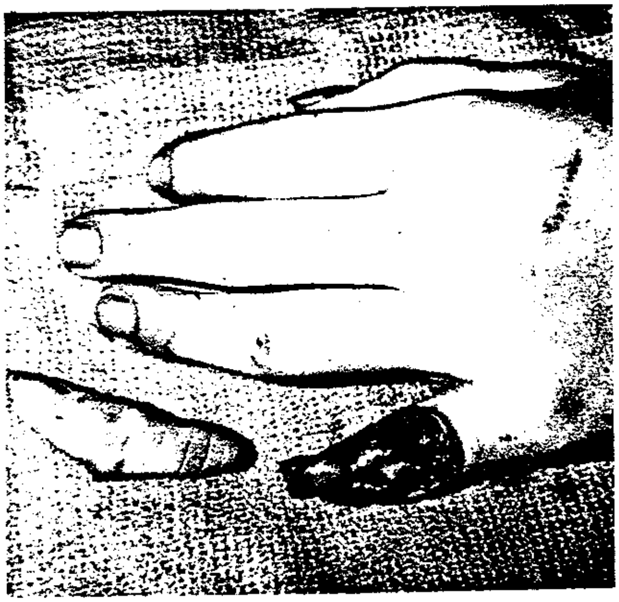

Figure 3A. A. K., a border finger amputation in a 14-year-old female with a ring avulsion injury of the non-dominant left fifth finger at the distal interphalangeal joint level and associated dorsal degloving proximal to the proximal interphalangeal joint.

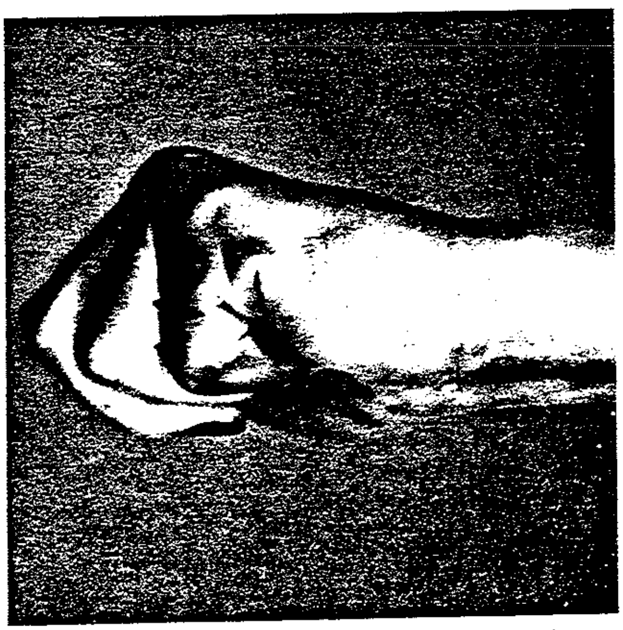

Figure 3B. Flexion 15 months postoperative.

Figure 3C. Extension 15 months postoperative.

can be covered with split-thickness skin grafts. A voluminous, nonconstricting dressing and a splint are applied; this leaves the distal part exposed and able to be monitored for viability, principally by color, refill action, and temperature. Diminished temperature along with whitish discoloration indicates arterial failure; bluish discoloration indicates venous failure. Circulation failure dictates that the patient be returned to the operating room or else the replanted part will be doomed to necrosis. Patients can begin protected movement in a few days. In four weeks, dynamic splints are applied, provided they do not interfere with bone fixation, which should be firm and strong from the start. Dynamic flexion is then alternated with extension to facilitate early movement and improve the eventual result (Figure 4A and 4B).

Results of replantation

For sharp amputations in patients who otherwise are good candidates for reattachment, the survival rate exceeds 95 percent. However, survival rate does not mean function, which should be superior to and certainly not less than what can be achieved with a prosthetic device; otherwise, the patient has been done a disfavor.

On the average, patients who have undergone a replantation have returned to work in 6.5 months, one month longer than those who have been treated by amputation-stump closure, fitted with a prosthetic device, and subsequently taught to use the device. Replantation patients can usually anticipate more than one operative procedure; on our service, an average of 1.6 operations per replantation are performed.

Initially, each replantation candidate must be carefully evaluated for the benefits that he or she might receive as a final result. Many times, distal parts are reattached to save a joint, such as the knee or elbow, and to ensure better function and less effort in manipulation of the prosthetic device.

Free-tissue transfer

There are many indications for immediate and delayed reconstruction of traumatic injuries of the limbs by microvascular free composite tissue transfer, especially in an emergency situation. Some of the indications are:

- To cover and salvage exposed tendon, nerve, joint, long segments of the blood vessel, and bone, particularly if fixation plates are exposed.
- As a simultaneous vascular conduit to the replanted part and as a free-tissue cover.
- Initially to provide superior circulation as well as sensation (the neurovascular cutaneous flap).

Free neurovascular flaps can be employed for emergency reconstruction. Skin of the first web space extending on the first and second toes was found to have sensation superior to the dorsalis pedis flap. O'Brien and Morrison of Melbourne, Australia, developed a thumb reconstructive procedure using bone graft wrapped with the neurovascular skin removed from three-quarters of the circumference of the large toe.[22] It is the most cosmetically appealing of any thumb reconstruction procedure. At the University of Louisville we have used it for emergency reconstruction of the thumb.

Recently, one of my associates reconstructed an avulsion of the proximal interphalangeal joint, including the overlying extensor tendon and skin of a

Figure 4A. D. J., major replantation. Bilateral arm amputations in a 19-year-old male from falling sheet metal in an open mine shaft. The right side amputated at mid forearm level, the left through the elbow. (From Kleinert, H. E. et al.: An overview of replantation and results of 347 replants in 245 patients. J. Trauma 20:390-398, May 1980.)

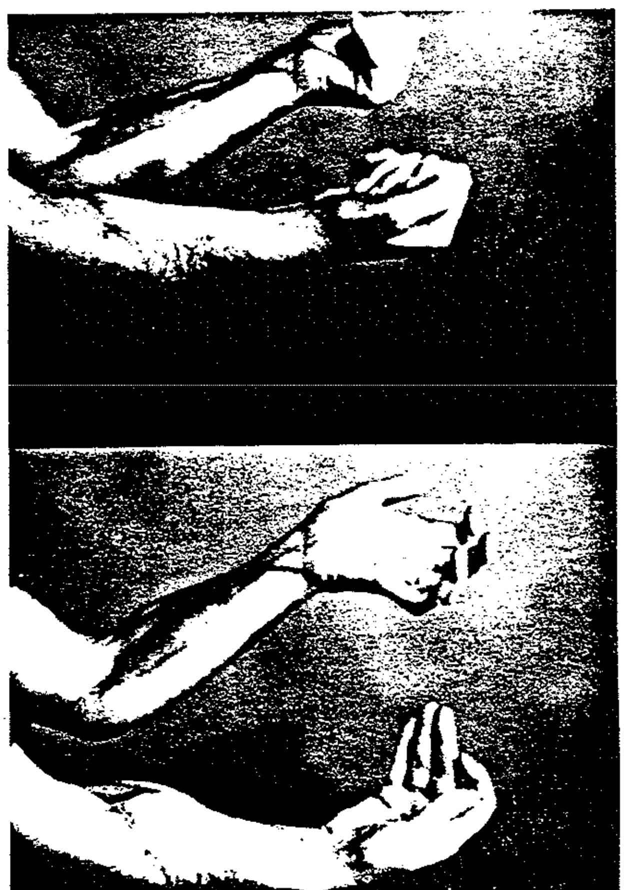

Figure 4B. Flexion and extension two years postoperative.

finger, by performing an emergency vascularized toe-joint transfer, including the necessary tendon and skin.

Free microvascular transfer of tissue necessitates careful preoperative selection of both donor and recipient sites. Operative and anesthesia time can be reduced by a two-team effort. Understandably the transfer is usually performed as a secondary or delayed primary reconstructive procedure, rather than as an emergency procedure, when all operative conditions are ideal.

Applications of free-tissue transfers

An excellent indication for a free-tissue transfer in the upper extremity is a short, poorly functioning thumb-amputation stump in the dominant hand. The advantages of toe transfers are obvious: the problem is solved in one operation and the reconstructed digit is superior to any conventional alternative. It has a joint, tendons, and a normal-appearing skin cover, which is interpreted as a thumb since nerves are attached to the proximal-thumb innervation. Motion and strength are excellent. Disadvantages include the fact that neither the first nor second toe is actually the proper size. The large toe is slightly too large, yet functionally and cosmetically it is superior to the smaller second toe. Transfer of the first toe creates a greater functional and cosmetic defect in the foot than does transfer of the second toe.

Toe transfer for digital reconstruction is indicated when all digits are amputated (Figure 5A and 5B). It may be a single- or double-toe transfer. Under some circumstances, a functional, but more likely a cosmetic, toe transfer may be indicated for the reconstruction of a distal amputation stump of a single finger. Small neurovascular flaps from the toe pads can bring increased blood supply to the fingertips as they restore the otherwise irreplaceable sensory pads of the digits, both functionally and cosmetically. Toe pads have the proper amount of fibrous tissue, sensory end-organs, matching skin color, and texture to reconstruct the tips of fingers. When necessary, the transfer can include the nailbed, which, since it is vascularized, will successfully reproduce a nail.

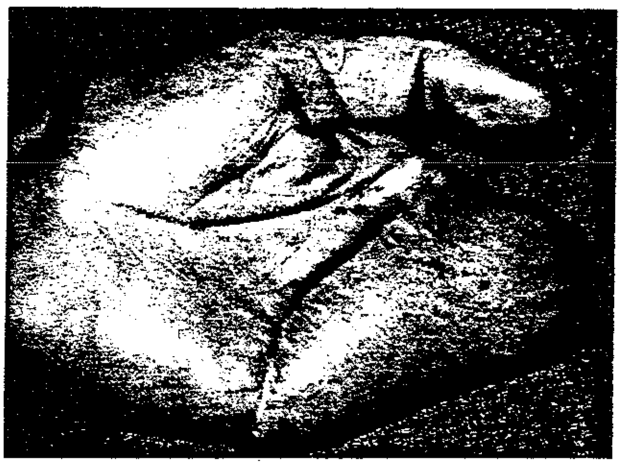

Figure 5A. *W. G., a 32-year-old male, sustained a severe crush injury to both hands requiring considerable reconstructive surgery. A pedicle groin flap was used for initial cover of the left hand, then free vascularized transfer of the left second and third toes to the third and fourth metacarpals was undertaken. (From Kutz J. E., Thomson C. B., Klein H. W.: Toe-to-hand Transfer. Chapter 18, AAOS Symposium on Microsurgery, pp. 227-253, C. V. Mosby Co., St. Louis, 1979)*

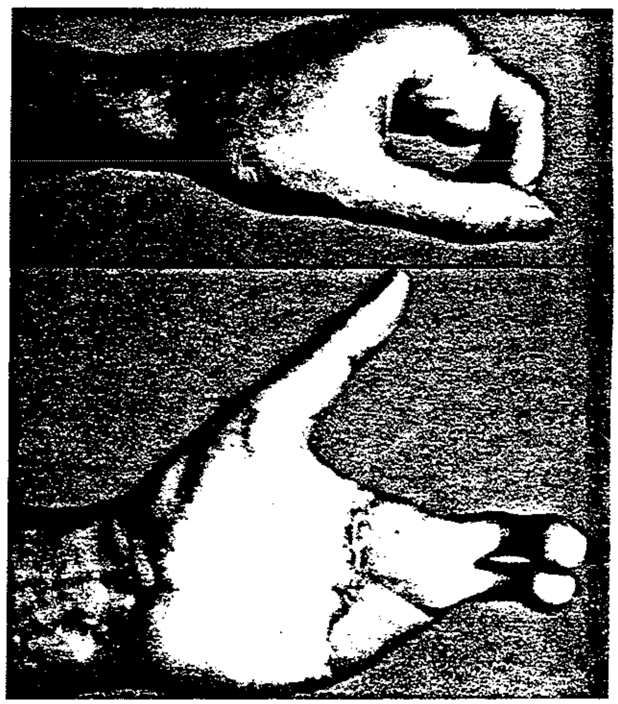

Figure 5B. *Function of the toe transfer three years postoperative.*

The first web space extending onto the adjacent aspects of the first and second toes, and if necessary onto the dorsum of the foot, forms a large neurosensory flap. Other donor sites for skin coverage that have variable sensory qualities besides the dorsalis pedis are the inferior epigastric, groin, intercostal, saphenous, deltoid, scapular, medial-arm, and forearm flaps (Figure 6A and 6B).

Myocutaneous transfers provide maximum soft-tissue coverage and increase the blood supply to the recipient site. When all muscle has been lost, as happens in some cases of Volkmann's ischemic necrosis and from electrical burns or avulsion of all flexor or extensor muscles, reconstruction may be possible by free neurovascular muscle transfer. Many donor muscles are present in the thigh. The "work horse" flap, the latissimus dorsi muscle, with its long vascular pedicle, is commonly used.

Free vascularized bone graft has added a needed dimension to orthopaedic surgery. Long segments of bone can be replaced. Nonunions that include avascular bone fragments are dealt with conveniently by more rapid healing of fracture sites, which results in less deformity than by conventional methods. Vascularized bone grafts that include skin as a composite graft to the tibial region have extensive application. An excellent donor site is iliac bone with overlying groin skin based on the deep circumflex iliac vessels.

Skin avulsed from the feet and legs can be difficult to replace, for example, in cases of exposed tibial fractures, exposed compression fixation plates, and chronic unstable scars on the anterior tibial surface. In the past, chronic osteomyelitis often necessitated multistage reconstruction procedures and, at times, amputation. Myocutaneous free-tissue transfer provides a stable cover and further increases the blood supply to a fibrotic scar area, which in turn promotes control of chronic infection and accelerates underlying bone healing.

Theoretically and in many cases clinically, bone avulsion with epiphyseal destruction in the young can and has been treated by transferring both metaphysis and epiphysis. Resultant deformity can be lessened or eliminated by maintaining longitudinal bone growth.

After more than one year of microsurgical laboratory research with monkeys, we have performed

Figure 6A. P. F., a 14-year-old male, lost the fifth toe with associated metatarsal and considerable plantar soft tissue in a shotgun injury.

Figure 6B. An innervated dorsalis pedis free flap from the contralateral foot provides excellent coverage.

several clinical cases of autogenous vascularized joint transfers from foot to hand. The principal indication is joint destruction accompanied by epiphyseal loss in a child. Immediately after bone or joint destruction, the length of the digit or metacarpus can be maintained by a silicone block. On removal of the silicone, the secondary bone or joint replacement has a ready recipient site. Overlying skin is transferred to indicate the viability of the underlying joint. As required, extensor and/or flexor tendon is transferred simultaneously.

"All surgical specialty training programs will include experience in and exposure to the principles of microsurgery."

Peripheral nerve regeneration

One of the greatest surgical problems is inadequate peripheral nerve regeneration after injury. Only the very young can expect near-normal function after nerve repair. However, even the best of results will exhibit some muscle and sensory loss. Application of microsurgical techniques combined with funicular nerve grafting to avoid tension on the repair site, as advocated by Hanno Millesi and others about 15 years ago, has improved results. Some patients with extensive nerve loss cannot be treated other than by nerve grafting.

A devastating accident that ordinarily affects active males in their prime of life is brachial plexus injury. Complete tears of the brachial plexus have doomed these patients to chronic pain and a flail limb or amputation. The hope of some return of function can be offered by brachial plexus exploration and nerve-grafting procedures.

The search for therapeutic improvement after human nerve injury has been relatively unrewarding. Experimental work has involved differential staining to identify motor and sensory fibers, nerve-growth stimulating factors, vascularized nerve grafts, and improved repair techniques. Sophisticated pre-, intra-, and postoperative nerve stimulators and recording devices that have recently become available have been of value.

Many scientifically allied investigators are involved in the advancement of microsurgery. Engineers and opticians continue to improve instruments and microscopes. Non-invasive methods of evaluating and measuring blood flow, such as the Doppler method, are of enormous help. Methods of monitoring postoperative circulation and evaluating tissue viability are of immeasurable value. Micro-instruments, microsutures, and microneedles continue to be improved. Twenty years ago these tools were available only in their crudest developmental forms.

The future

What does the crystal ball of the future offer for microsurgery? I believe so far we are looking only at the iceberg's tip. The human hand can respond to and perform any task the eye can see. New microsurgical techniques and procedures will develop in all surgical specialties. The general surgeon will do free microvascular intestinal transfers for esophageal and other gastrointestinal replacements, and biliary and pancreatic surgical results will be improved. Furthermore, organ transplantation will be included in the general surgeon's armamentarium.

Orthopaedic surgeons will do more free neurovascular muscle transfers. Replacement of the epiphysis will be more commonplace and will be used to correct congenital absence of the radius and other problems, such as Madelung's deformity. Avascular bone necroses, particularly in the acute stages and probably including Legg-Calve-Perthes disease, Kienböck's disease, and even impending necrosis of the femoral head, will likely be treated by revascularization.

Joint transplants will be more commonplace, particularly among the young. If tissue-matching problems are solved, homotransplantation of joints and limbs will become a reality. Congenital defects, such as aphalanga, are already treated by toe transfers used for both thumb and finger. The future may include limb-bud transfers for congenital amputations.

Such potentially prolonged procedures have been made possible through advancements in regional and general anesthesia. Doubtless these developments will continue in synchrony.

For the plastic surgeon the sky is the limit. Additional free-tissue donor sites will be developed from all parts of the body. The Chinese recently developed the radially based forearm flap. Within the past year, Marko Godina of Yugoslavia demonstrated to me the use of a new medial brachial neurovascular free flap to close a foot-amputation stump.[23] After primary closure, the resultant scar was minimal. Free-tissue transfer donor sites have customarily been moved from the lower to the upper extremity. The Foot Society will be happy to see them moved the other way.

Neurosurgeons employed microsurgery as early as 1960. Results from traumatic, vascular, and tumor operations on the central nervous system have improved greatly. The central nervous system, once damaged, does not heal; however, hope remains that an answer to this problem can be found. In urology and gynecology microsurgery is used to reconstruct the ureter and the urethra as well as to reverse sterilization procedures. Reconstruction by microneurovascular free tissue and composite tissue transfer has virtually unlimited application.

All surgical specialty training programs will include experience in and exposure to the principles of microsurgery. The effect will be a dramatic expansion of microsurgery to improve both emergency and elective care of the patient.

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