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Reconstructive Microsurgery

Konstantinos N. Malizos

v a d e m e c u m

Reconstructive Microsurgery

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Dedication

This book is dedicated to three distinguished physicians who have made a very significant contribution to the development of microsurgery. They have been devoted teachers in residency programs and at internationally acknowledged training centers in hand surgery and reconstructive microsurgery.

Panayiotis N. Soucacos, MD, FACS, Professor and Chairman of the Department of Orthopaedics at the University of Ioannina, laid the foundations for microsurgery in Greece in the early seventies. In the last 25 years he has trained and inspired hundreds of residents in the operating room, in seminars and in workshops for microsurgery. He is a natural teacher. He was awarded the prize for "Exceptional Academic Teaching" in 1997. His amicable, honest and gentle personality, as well as his attitude to scientific work and to academic life, have had a great influence on many Greek Orthopaedic and Plastic surgeons enabling them to realize that expertise in Microsurgery is an extremely valuable tool in their work. Under his leadership a number of young and motivated orthopaedic and plastic surgeons, mostly his first trainees, laid the foundation of the Hellenic Society for Reconstructive Microsurgery.

After several years of work with him and during my training in Microsurgery I met another very important surgeon and great teacher, Guy Foucher, MD, in Strasbourg, France. He is an extraordinary surgeon internationally renowned for his exceptional surgical skills. At a very young age he became one of the pioneers in the introduction of "ambulatory" hand surgery in Europe, with his unit "SOS MAIN Strasbourg". Many fellows and residents have completed their training at his center and had the opportunity to benefit from his vast knowledge in the field of hand surgery. He was capable of combining the administration of his unit, hundreds of operations every year, together with clinical research, writing dozens of publications and travelling to international congresses and meetings. The knowledge and experience he shared with a large number of young trainee surgeons at "SOS MAIN" in Strasbourg is hard to assess.

Concluding my post-residency training in the United States, I was honored to work under the sponsorship of James R. Urbaniak, MD, who has made an immense contribution on the current level of microsurgery. In his program at Duke University Medical Center the level of training in orthopaedics, hand surgery and microsurgery is unsurpassed. Those of us who have had the exceptional opportunity to work with him have experienced his "human" qualities, his gentle manners, his patience and willingness to spend whatever time it took to explain a complicated problem or technique. He is an excellent teacher and is willing to share his operative secrets. A unique academic personality with unparalleled devotion to research. He continuously searches for new solutions, alternative treatments and advanced techniques in laboratory investigations. These accomplishments have been awarded with the highest prizes from national and international scientific societies.

This handbook, composed from the knowledge and experience of the contributors and myself, pays tribute to my teachers and all the readers.

Konstantinos N. Malizos, M.D.

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Preface

Dear Reader,

Microsurgery, in other words performing surgery on miniature anatomical structures, was made possible in the second half of the 20th century, when technology allowed development of operative microscope, micro-instruments and micro-sutures made it possible. It started as an advanced surgical technique and its first application was the replantation of amputated digits. This fascinating surgery transformed what was once thought of as a miracle into reality. Various disciplines have been brought together in the "World of Microsurgery" and it is now possible to replant, implant and transplant tissues or part of the extremities. Human anatomy has been re-evaluated in the light of new possibilities in microsurgery, in the search for vessels suitable for free tissue transfer.

In this work the classical techniques for microvascular anastomosis are briefly described, while the operative technique for the coaptation of the peripheral nerves complemented by more recent alternatives for the repair of short gaps are thoroughly described and illustrated.

Replantation of amputated fingers or major limb segments is a wide field for the application of microsurgical techniques. The current operative protocols for replantation of the amputated fingers and limbs at more proximal levels are described in detail. In the extremely rare cases where other body parts as the ear, the nose or the genitalia are amputated, replantation should be attempted following the same principles. In the lower extremities clear cut amputations are relatively uncommon. In clinical practice the question of attempting revascularization and salvaging rises when the surgeon is faced with an open type IIIC fracture of the tibia or the foot. The different aspects of this controversial issue are presented in separate chapters, for example the mangled upper extremity and the type IIIC open fractures of the lower extremity.

Reconstructive Microsurgery today has opened such a broad spectrum of applications that it reflects the words of J.R Urbaniak, MD, many years ago "..the world of microsurgery has no end..". Free tissue from skin, muscle, bone, fascia, periosteum, nerve or combinations of two or all of the above mentioned tissues can be transferred to cover defects of the teguments, missing bone or a lost muscular unit in the extremities, the face, the head and the neck. In a separate chapter concerning skeletal reconstruction we have given a relatively extensive description not only of the commonly utilized vascularized bone grafts but also of the special techniques proposed for the reconstruction of the skeleton after tumor extirpation. A special reference is made to the techniques of growing bone transfer which have successfully been applied in children suffering from intra- or para-articular bone loss. The new alternatives for the microsurgical management of the congenital malformation of the hand are also discussed in a separate chapter.

One of the fields where microsurgery has contributed with valuable treatment options is the brachial plexus. Nerve grafting, nerve transfer and neurotization now offer a considerable improvement to the outcome of these debilitating injuries. The last chapter is devoted to the current protocols applied in the management of peripheral lymphatic disorders. Microsurgical treatment is more efficacious than other alternatives not only in acquired lymphedema but also in primary lymphostatic pathology in children and adults.

If all the aforementioned show what has been accomplished in microsurgery today, we believe that as soon as the problems arising from allograft tissue rejection are overcome with progress in immunosupression, chimerism or new organ production with cloning, the unlimited horizon for "spare part" surgery will open up endless possibilities for reconstructing not only the defective part but also overcome the aging or degeneration of parts of the human body!

When writing and editing this handbook we had in mind the needs of a young trainee in orthopaedic, plastic or general surgeon for a practical guide and a quick reference for daily management issues where microsurgery may provide a solution. Personalized or center-specific preferences in treatment protocols and management strategies are expressed as in all scientific fields; however they may differ substantially between centers only in a few issues, i.e., the management of brachial plexus injuries. We hope to have creative criticism from our readers. Suggestions for new fields to be covered, new techniques or microsurgical treatment alternatives will be welcome.

We look forward to hearing from you,

The Editor

Acknowledgments

The editor would like to express his deepest appreciation, also on behalf of the contributors, to Mrs. Konstantina Papastefanou, for the coordination and the secretarial support, the dedication and the excellent professional cooperation she has given to the completion of this project.

This work wouldn't have been possible without the support of Dr. Vaughan Bowen, MD, FRCS(C), MBChB., to whom I would like to express my sincere appreciation and warmest thanks.

Chapter 1

Microvascular Surgical Techniques

Toni Zhong, C. Vaughan A. Bowen

The common basis of all microvascular surgery is the ability to repair very small blood vessels. Once the technique is mastered it becomes possible to revascularize and replant incomplete or complete digital amputations, and to design free tissue transfer procedures for the reconstruction of a large variety of different types of damaged parts. Historically, the challenge was to find a way to repair vessels one millimeter in diameter with predictable postoperative patency.

Historical Background

The early history of blood vessel surgery was reviewed by Wintermantel.[1]

Some of the first surgical instruments and operative procedures for blood vessel surgery were described by Stromayr, in 1559, and Scultetus, in 1666. In 1889, Jassinowsky summarized the essential points of suturing arteries in animals. Abbe, in 1894, used glass tubes for vascular grafts in dog femoral arteries and cat aorta. In 1897, Nitze described an ivory prosthesis for vascular anastomoses and Murphy proposed a new method for arterial repair that he called 'invagination', the first sleeve anastomosis. In 1899, Silberberg wrote a doctorate thesis on clinical and experimental research in vascular sutures. At the end of the 19th century, pioneering surgeons such as Alexis Carrel and Peyr not only demonstrated the feasibility of vascular anastomosis with predictable patency rates, but also developed the techniques, some of which are still employed today.

Improved anaesthetic techniques and the introduction of antibiotics were important factors that have allowed more complex surgical procedures to be developed in the 20th century. The search for more sophisticated instruments and suture materials for vascular surgery began in the 1940s, in response to the large number of vascular injuries that occurred during the World War II. Clinical success rates in major vascular surgery significantly improved at this point, although the repair of peripheral vessels, smaller than 2-3 mm in diameter, was still associated with a high incidence of intravascular thrombosis.

The solution to the problem of small vessel repair was to use magnification, a technique used by ENT surgeons since the 1920s and adopted by eye surgeons in the 1940s. Four factors were found to be essential for the success of repairing blood vessels with diameters of 1.0 millimeter or less:

a. high magnification should be achieved with the operating microscope
b. delicate handling of the tissues with fine instruments
c. a satisfactory technique for microvascular coaptation
d. special microsutures.

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Microvascular Anastomotic Techniques

A large number of different techniques have been investigated for making microvascular anastomoses. Additionally, varying clinical situations demand that microsurgeons are familiar with a variety of different methods for making microvascular anastomoses. Techniques can be classified into two main categories:

a. type of anastomosis
b. method of fixation.

Type of Anastomosis

Microvascular anastomoses can be classified according to the technique used for their construction:

a. end-to-end anastomosis
b. end-to-side anastomosis
c. end-to-side branch anastomosis
d. end-in-end anastomosis
e. cuffing techniques.

End-to-End Anastomosis

The end-to-end anastomosis was the first technique used and remains the most widely applicable. Ideally the two cut vessel ends are held loosely together in a double approximating microvascular clamp; anastomosis is then made by first securing the front wall and then rotating the clamp to facilitate repair of the back wall. In awkward clinical conditions where it is impossible to rotate the clamp, it is necessary to use the back wall or side wall technique.

End-to-Side Anastomosis

The end-to-side anastomosis has been important for the revascularization of free tissue transfers. Godina[2] recommended it as the method of choice for arterial anastomoses when free flap transfers are used in lower extremity reconstruction. He attributed the following advantages to end-to-side anastomosis: a high success rate, preservation of all existing vessels in the injured extremity, allowance of greater freedom in operative planning, and provision of direct access to the vessels ensuring technical simplicity.

End-to-Side Branch Anastomosis

The technique of end-to-side branch anastomosis is a modification of the end-to-side anastomosis, in which an arterial branch or venous tributary, located at the selected anastomotic site, is used as a recipient site vessels. The donor vessel is anastomosed to the side branch using a conventional end-to-end technique. This method of anastomosis, if available, may be preferable to an end-to-side technique, especially if clinical conditions are sub-optimal.

End-in-End Anastomosis

The end-in-end intussusception method, originally known as the sleeve anastomosis, was introduced into microsurgery by Lauritzen.[3] This technique requires the upstream vessel to be placed inside the downstream vessel to make an overlap, or sleeve, in order to prevent leakage. Proponents of the technique feel that it is superior to end-to-end sutured anastomosis because:

a. it is faster,
b. there is less intimal dissection,
c. aneurysms at the anastomotic site have not been reported, and
d. resistance to irradiation is greater. In some parts of the world, microvascular surgeons use this technique almost exclusively. Elsewhere, surgeons do not use it because they have found it difficult to reproduce the reported high patency rates and low complication rates.

Cuffing Techniques

Early on, cuffing techniques were often used to prevent small leaks at the anastomotic site. This practice is no longer observed. Today, we understand that small leaks rapidly resolve by themselves and large leaks can be stopped by the addition of extra sutures into the adventitial layer.

Method of Fixation

Many methods of anastomotic fixation have been investigated since surgeons first started using microvascular techniques. The goal has been to find simpler and faster techniques without decreasing patency rates. Some methods have been more successful than others.

Described anastomotic fixation methods include:
a. sutured anastomoses
b. laser techniques
c. electrocoaptation
d. mechanical devices
e. adhesives anastomoses.

Suturing is the most versatile method for making microvascular anastomoses. It can be used in any clinical situation, whether technically straightforward or in very awkward situations.

Sutured Anastomoses

The technique of suturing microvascular anastomoses has been widely used since Jacobson and Suarez[4] first reported their successful results in 1960. Suture technique has made great progress since that time and remains the most widely used method of fixation. Many variations of sutured anastomoses have been described. These can be thought of as falling into two categories:
a. different kinds of suture material
b. varying methods for placing the sutures.

The goal is to coapt the vessels with minimal risk of intravascular thrombosis.

Decreased blood flow, alterations in blood constituents, and vessel wall damage are the three main factors that lead to intravascular thrombosis. Thus, when a microvascular anastomosis is made, the aim should be to join the vessels in such as way that minimal disturbance to the vessel wall is 'seen' on the lumenal side.

Suture Materials

Over the years, as surgical technique became finer, suture materials that were equally small and delicate were developed. Nylon (a generic name referring to a family of amide polymers) was found to be the best suture material. It is easy to use, satisfactory in tensile strength, causes very little tissue reaction, and narrow diameter strands are relatively straightforward to manufacture. Researchers have investigated the use of other types of suture material. Phelan et al[5] compared sutures made out of silk, nylon and dacron. They demonstrated that dacron and nylon were superior to silk, but experienced difficulty in tying the knots.

Needle construction was the biggest problem in the manufacture of microsutures. Microneedles needed to be sharp tipped, smooth bodied, adequately shaped for ease of handling, and smoothly swaged to the suture material. In the early days, small needles of different sizes, shapes and materials were tested but all were invariably too big, and resulted in hemorrhage from the large holes left in the vessel walls. Improvements in needles used in microsurgery resulted from a rapidly expanding industry in microsuture production. The small S & T Chirurgische Nadeln firm (S & T after its founders W. Springler and G. Tritt) in West Germany became the leader in the innovation of microsutures. Working closely with Acland, they produced needles that were considerably sharper and smaller than those of their competitors. Since size of the needle hole in the vessel wall is an interplay of two factors: needle sharpness and needle diameter, the new S & T needles had effectively solved the vessel wall hemorrhaging problem.

The medical literature contains many publications on the subject of microsutures: For instance, Pitt and Humphries[6] compared sutures of 10-0 nylon on a taper pointed needle with similar sutures on a new micro edge taper needle. They found that while the patency rates were similar for the two needles, the new needle caused less damage to the intima.

Nowadays, microsutures are made by initially swaging fine nylon suture material onto straight microneedles, and then curving the needles by machine. Needle points are extremely sharp, blades are tapered, bodies are smooth and fine, and the swages are secure. Most surgeons use a 9-0 or 10-0 suture on a 100 or 70 micron needle for microvascular anastomoses, although an 11-0 suture on a 50 micron needle is also available for very delicate work.

Methods for Placing Sutures

In a sutured microvascular anastomosis, the surgeon should aim to achieve a leak-free anastomosis with as few sutures as possible.[7] Adherence to this principle minimizes problems associated with medial necrosis and arterial occlusion. Sutures should pass through the full thickness of the vessel wall as this probably causes less media disruption than sutures that pass only partially through the wall. The vessel ends should be closely approximated, and care should be taken that the tissue encompassed by the sutures is not strangulated.

Good suturing technique is critical to the patency of the vessel postsurgery. Technically poor suturing results in narrowing of the lumen at the anastomotic site, distortion of the vessel wall, and an increase in the likelihood of vascular thrombosis. Sutures must be placed evenly and spaced correctly. Harashina noted that the last one or two sutures are the most critical to the success of the anastomosis. They are technically challenging as the lumen may not be clearly visible through the gap. To circumvent this problem, he recommended leaving the final two or three sutures untied until suture placement is complete.

Conventionally, a double approximating microvascular clamp is used to approximate the ends of the vessels being sutures. Sutures are then placed in an orderly manner. In the early days a triangulation method was used for suture placement. Nowadays, most surgeons prefer a biangulation technique; initially placing two stay sutures 180 degrees apart. Interrupted sutures are then inserted between them, repairing the front wall first. When this is complete, the clamp is used to rotated the vessel, presenting the back wall for suturing. Sutures are placed about 0.3 millimeters apart (eight stitches for a 0.9 mm-1.0 mm vessel) in a manner that is sometimes known as the 'ship's wheel' technique.[9] Sutures should tied with a conventional three throw surgeon's knot.

Many variations are used. Technique is a personal preference and varies a great deal from place to place. Some surgeons prefer back wall technique as this can be used in every clinical situation. Side wall technique may also be useful in certain awkward situations. Continuous suturing has also been investigated. Patency rates between the different methods are comparable. Each has advantages and disadvantages. For instance, continuous suturing is a faster technique, but the problems associated with entrapment and breakage of the suture material on the microvascular clamps probably outweigh the benefits.

A number of technical aids have been developed to help surgeons achieve maximum accuracy with their suturing. A surgeon working alone or with a less skilled assistant may find Acland's frame clamps useful for holding the long ends of key stay sutures. A surgeon working with an experienced assistant usually prefers to have the assistant apply tension to the key stay sutures so that the anastomosis is optimally positioned for insertion of the next suture. In cases where the assistant is highly skilled and the anastomosis is not in a difficult location, a great deal of time may be saved by using the two surgeon-two needle technique.

Laser Anastomoses

Some investigators have attempted to weld blood vessels together using laser beams. The intense monochromatic light of a laser beam produces heat on absorption. A "spot weld" is accomplished by thermally induced coagulation necrosis at the site of application. The most widely used laser beams are the argon laser, the Neodymium:YAG (yttrium-aluminium-garnet) laser, the CO_2 (carbon dioxide) laser, and the thulium-holmium-chromium:YAG (THC:YAG) laser.

Jain[10] has investigated the use of the Neodymium:YAG laser for the repair of injuries to small arteries, and he reported that laser end-to-side anastomosis had many advantages over suturing. They were fast to use, no sutures to act as foreign bodies, no needle passage trauma, less variance of results due to different skill levels of the surgeon, and it could reach deeper parts of the body not easily accessible to sutures. Bailes et al[11] found, in their histological studies, that the healing process of laser assisted microvascular anastomoses did not differ from that seen with other techniques. Other researchers have investigated the use of a CO_2 laser. Although both techniques yielded similar patency results, aneurysm formation was a consistent problem.[12] The argon laser has also been used to for making end-to-end vascular anastomoses. While argon laser has the advantage of emitting visible wavelengths of light, its tissue effects have been unpredictable.

Despite the optimism of some researchers, the use of lasers for microvascular anastomoses has not been generally accepted.

Electrocoaptive Microvascular Anastomoses

The principle behind electrocoaptive microvascular anastomosis is to produce an adherent and localized coagulum by the passage of high frequency electric current through the adjacent tissues. The current is applied to the anastomotic site with the aid of bipolar electrode forceps.

The major problem with the use of electrocoaptation methods is difficulty in determining the correct amount of electrical current necessary to produce just the right amount of coagulation. Investigators have determined the amount of electrical current by trial and error using animal vessels.

The technique has not been widely used. For electrocoaptive microsurgical anastomoses to become clinically feasible, there needs to be

a. better understanding of the electrical welding mechanism and
b. development of better equipment.

Mechanical Anastomotic Devices

Staplers and couplers have been used both experimentally and clinically for vessel repair for a long time. The devices investigated can be classified into three types:

a. individual circumferential metallic staples,
b. everting pinned ring devices, and
c. extra-lumenal cuffs and bushings.

In general mechanical devices have not been accepted for widespread use. In the laboratory, they have been shown to produce rapid and successful methods for microvascular anastomosis but, in almost all cases, they have been technically difficult to use. The staplers are too large for manipulation under the operating microscope; the pinned ring devices require considerable experience and trained assistance; the coupling devices use excessive vessel length to achieve satisfactory eversion at the anastomosis, and accurate selection of the correct size of coupler is difficult.

The most successful mechanical technique is the 3M coupling device. This is a pinned ring device, developed from the Scandinavian UNILINK apparatus. It is now commercially available. Clinical series reporting the successful use of this device have been published.[13]

Adhesive Anastomoses

A number of different types of adhesive microvascular anastomoses have been investigated. These include cyanoacrylic adhesives, polyurethane resin, adhesive tapes, and fibrinogen adhesives.

Most of the studies on adhesive anastomoses used cyanoacrylic adhesives. Cyanoacrylate is formed by the polymerization of monomers, which can be represented by the chemical formula $CH_2{=}C(CN)COOR$. The addition of water, normal saline, or weak bases initiates a reaction that leads rapidly to stable bond formation on a variety of material surfaces. Cyanoacrylate adhesives coapt the vessels satisfactorily. They have not become available for general clinical use, however, because of their potential to generate severe inflammatory reactions and the fibrosarcomas found in some laboratory animals after their use.[14]

Fibrinogen adhesive is used for many purposes in surgery. It can be used for making microvascular anastomoses, but is not widely used for this purpose.

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Microsurgical Techniques for Peripheral Nerve Repair

Bruno Battiston, Pierluigi Tos

Introduction

Nowadays, surgical resolution of a disability resulting from a peripheral nerve lesion is no longer an impossible task for the surgeon even if diagnosis and treatment still require a thorough knowledge of the pathophysiology of the nervous system together with the most recent sophisticated microsurgical techniques. Basic knowledge of the pathophysiological processes in a nerve trunk and its neurons after transection injury (degeneration and regeneration) is essential in order to choose the correct surgical treatment, its timing and the rehabilitation program.

Since the observations of Waller[1] in 1850 describing the changes of the distal segment of a transected nerve in the frog, there has been extensive research and numerous studies. However, only in the seventies did this lead to the fundamental works of Millesi on nerve repair by means of interfascicular nerve grafting.[2] Two decades have now passed and we are able to understand the rules of nerve regeneration better, also thanks to the studies by Rita Levi Montalcini, Lundborg and other researchers on nerve growth factors, chemotropism and many other fields of interest.[3-5] There are, however, a lot of unknown mechanisms over which the surgeon can have no control in the effort to obtain good nerve healing and better clinical results.

Nerve Lesions

As far as nerve anatomy and the classification of nerve injuries is concerned we may look at the classic works by Seddon,[6] Sunderland,[7] Dellon[8] and Lundborg[9] and others.

From a clinical point of view, nerve injuries may be classified in various ways depending on the etiology (mechanical, thermal, ischemic, chemical) and on the way they arise (acute, chronic) the most frequent being the acute post traumatic lesions presenting an increasing incidence, due to road and work place accidents. The effects of a traumatic lesion on a nerve may be divided into 6 groups as classically stated by Sunderland (Table 2.1). Here we will examine the microsurgical reconstruction of severely damaged nerves, unable to obtain a spontaneous recovery.

The surgical treatment of these lesions must take into consideration the various factors which condition nerve regeneration. Therefore, the different techniques of nerve repair are described through the analysis of these factors together with the indications for the treatment of peripheral nerve injuries.

Table 2.1. Classification of nerve injuries

Seddon	Sunderland (degree)	Myelin	Axon	Endoneurium	Perineurium	Epineurium
Neurapraxia	I	+	–	–	–	–
Axonotmesis	II	+	+	–	–	–
	III	+	+	+	–	–
	IV	+	+	+	+	–
Neurotmesis	V	+	+	+	+	+
	VI Various fibers and fascicles demonstrate various pathologic changes (MacKinnon-Dellon, 1988)					

Factors Influencing Nerve Regeneration

Six groups of factors, which influence nerve regeneration, and consequently, the final result of a nerve repair may be distinguished, i.e., general factors, type and site of the lesion, timing, coaptation technique, biomolecular factors.

General Factors

In this group we include such parameters as the patient's age and general health.

The age of the patient is a very important prognostic factor. It is well known that children generally have better functional recovery than do adults. This is due, in part, to a more valid nerve regeneration, but overall to an easier recovery of the body scheme thanks to a greater plasticity of the central nervous system. Indeed, some authors have reported the best results to be obtained in patients under 20 years of age.[11]

Associated diseases may influence nerve regeneration such as diabetes, metabolic dysfunctions, as well as does the use of alcohol or drugs.

Type of Lesion

When the nerve is injured along its trunk, regeneration is also influenced by the lesion margins, surrounding tissues and nerve substance loss. We will also examine special types of lesions: avulsion injuries.

Lesion Margins

A neat lesion leads to better results, while crushed stumps, even if well repaired, will give fibrous reaction inside the nerve with a consequent difficult nerve regeneration. The contused nerve stumps must be excised and a good trimming is essential.

Surrounding Tissues

After its reconstruction the peripheral nerve must be kept in a soft and well-vascularized bed. If the lesion is associated to skin problems or necrotic surrounding tissues, the best possible local conditions have to be created with the use of local or distant flaps

Nerve Lesion with or without Substance Loss

When a nerve has been damaged by a clean cut or when a crushed injury may be transformed into a neat one without sacrificing too much nervous tissue, a direct suture can be performed. Literature has described numerous techniques of nerve suture (epineurial, perineurial, epiperineural, etc. see Fig. 2.1). We shall describe the technical details while enumerating the technical factors influencing regeneration. On the contrary, the loss of nervous tissue must be repaired by the use of grafts and since the studies carried out by Millesi the use of interfascicular nerve autografts represents the "golden standard" for this kind of lesion (Fig. 2.1E).[2] Nerve grafts bridge the gap, guide regeneration and protect axons against the surrounding scar. Indeed, the introduction of nerve grafting greatly improved both the possibility and results of nerve surgery, even if, in the presence of a nerve gap over 10 cm, prognosis is poorer.[11] Generally, we use the sural nerve as the donor nerve, or, in some cases, other pure sensory nerves such as the medial cutaneous nerve of the arm or forearm, or the posterior interosseous nerve at the wrist. However, this creates a damage in a sound area (skin scar, sensory loss in the donor area, risk of neuroma formation); moreover, at times these autografts are not long enough to repair the nerve gap. This is why a number of authors looked for new techniques and tried to fill the nerve gap with "tubes". The use of tubes (synthetic or biologic such as veins or muscle) are able to guide the axonal regeneration without sacrificing sound nerves (Fig. 2.1F). We shall examine the advantages and problems of this kind of reconstruction while describing the influence of biomolecular factors on nerve regeneration. Although the use of nerve "allografts" could solve the problems from the nerve grafts donor site, the need for immunosuppression and the poor results of the few clinical experiences to date keep this technique, at least for the moment, in the experimental field.[12] In fact, allografts appear to function only as long as the immunosuppressed state is maintained as the tissue surrounding the host axons remains allogenic and once immunosuppression is stopped rejection and loss of the regained nerve function follows. If continuous research leads to better drugs with a lower toxicity, the use of allografts would then become a viable alternative. Some authors described, and used for some years, "vascularized" nerve grafts.[13] Microsurgical transfer of whole nerve segments with their vessels allows the grafting of nerve lesions even in avascular beds regardless of graft diameter. This should guarantee an improved blood supply at the nerve injury site with consequent rapid revascularization of the interposition nerve grafts and a better axonal regeneration. However, even those authors who initially reported quicker recoveries compared to traditional small avascular grafts, no longer use this technique as its real advantages do not justify the complexity of this surgery.

Lesion in Continuity

This is the most challenging of all nerve lesions often combining all or many of Sunderland's five degrees of injury. This represents a dilemma for the surgeon as it involves a mixed injury pattern in the various fascicles of the nerve with normal function through some of them and varying degrees of injury in others (Fig. 2.2A, 2.2B). The macroscopic appearance of the nerve (i.e., presence of scar tissue) may help the surgeon but intraoperative electrodiagnosis (electrical nerve stimulation or PESS) is also helpful. The surgeon must take great care not to injure intact fascicles, while the fourth and fifth degree injury patterns will require surgical reconstruction (excision and grafting) (Fig. 2.2C, 2.2D).

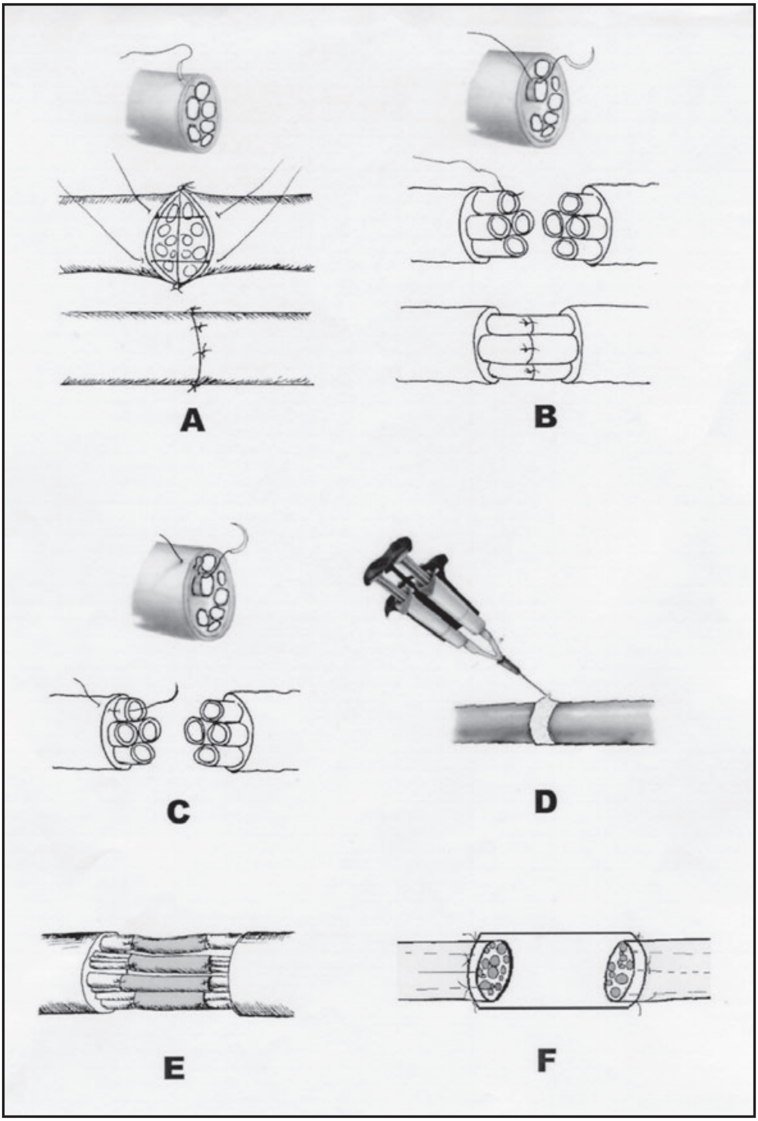

Fig. 2.1. Different techniques of nerve repair. A: Epineural suture. B: Perineural suture. C: Epiperineural suture. D: Reconstruction by fibrin glue. E: Interfascicular nerve grafting. F: Tubulization

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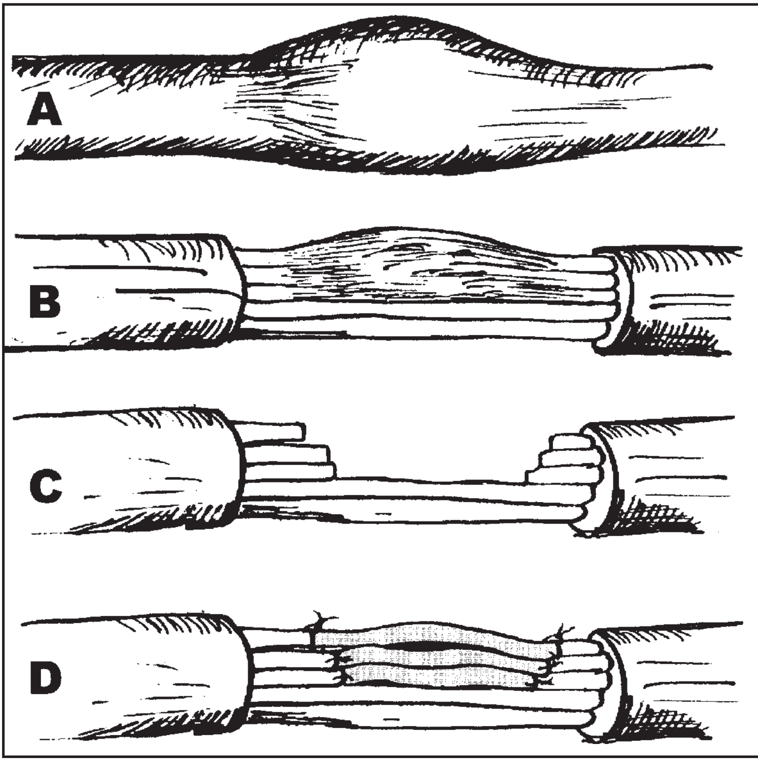

Fig. 2.2. A, B: In continuity lesion (Sunderland's 6th degree). C: Excision of damaged fascicules. D: Partial nerve reconstruction

Avulsion Injuries

The nerve may be avulsed at its origin from the spinal cord or when it comes into contact with the final target (muscle or sensory receptors). These lesions cannot be repaired by means of sutures or grafts.

In the case of root avulsion Carlstedt recently proposed the reimplantation of the roots into the spinal chord.[14] For the moment this is an experimental technique: it has been utilized by Carlstedt only in selected cases and the evaluation of the results is still in progress. Several authors have described the use of adjacent functioning nerve trunks as central donors to be coapted distally to the injured nerves. In these lesions various nerves can be used for "neurotization": intercostal nerves (generally to reconstruct the musculocutaneous nerve),[15] the XI cranial nerve or the cervical plexus,[16,17] controlateral C7 root,[18] some funiculi of the ulnar nerve for the musculocutaneous nerve.[19] We have reported a neurotization technique that is not used for avulsion injuries but rather to improve the results of proximal ulnar nerve lesions.[20] We use two final branches of the median nerve (the thenar sensory branch and the motor branch for the pronator quadratus muscle) to neurotize the ulnar

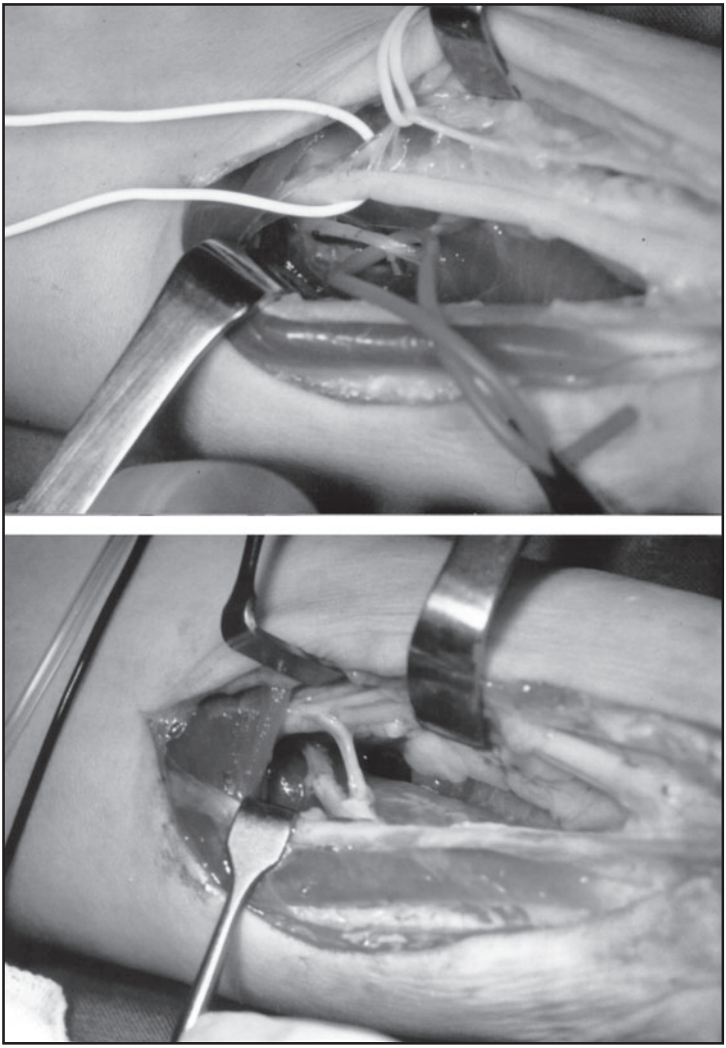

Fig. 2.3. Median to ulnar nerve neurotization. A: The sensory and motor branches of the median nerve are prepared. B Neurotization of the ulnar nerve by means of the two branches.

nerve at the wrist thus obtaining a distal, topographical reconstruction with faster recovery (Fig. 2.3). Recently, a new technique of nerve repair has been described to solve avulsion injuries: the "end to side" coaptation. The coaptation of a distal severed nerve stump laterally to an intact neighboring nerve gave good functional recovery

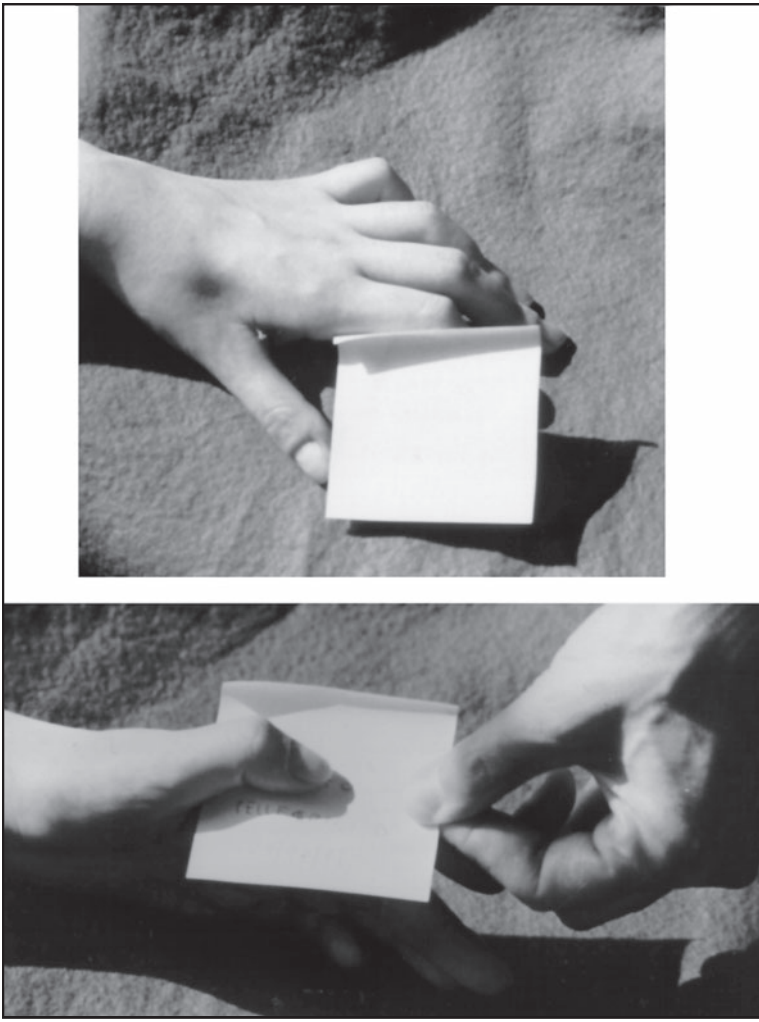

Fig. 2.3. Median to ulnar nerve neurotization. C: ulnar nerve palsy following complex lesion above the elbow. D: Positive Froment sign.

in several experimental works,[21] and some clinical reports[22] seem to suggest a promising role for this technique in special selected cases.

When the nerve has been avulsed from the muscle, Brunelli[23] utilizes the "direct muscular neurotization" with direct implantation of the nerve into the muscle (Fig. 2.4). The idea of a distal implantation is sometimes used even in patients with denervated skin areas (direct sensory neurotization).[23]

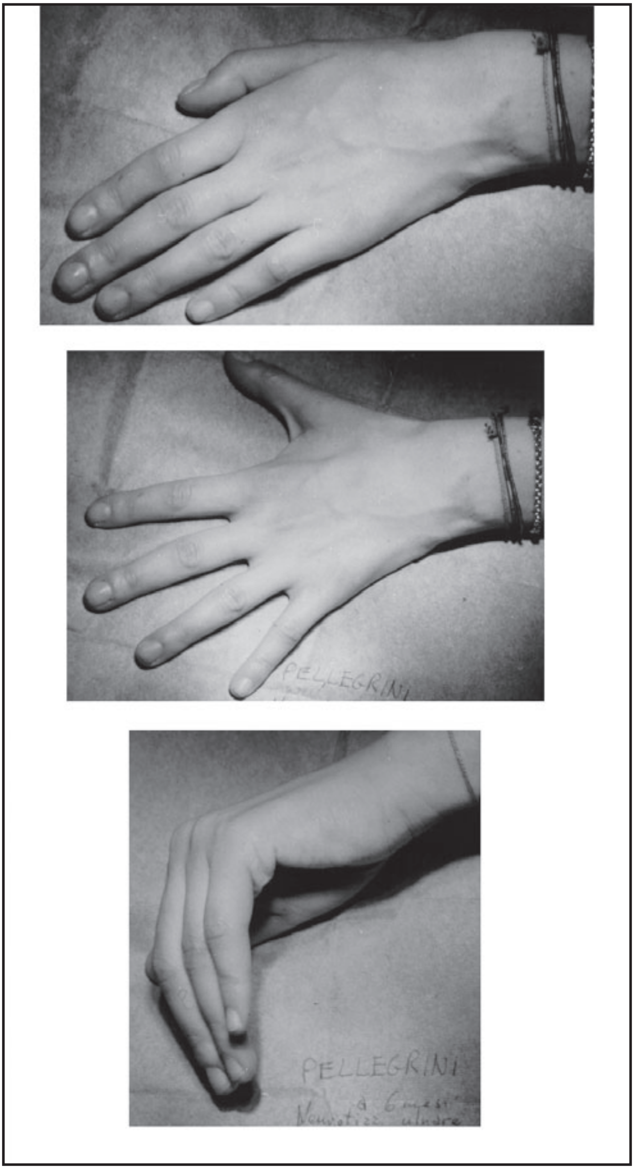

Fig. 2.3. Median to ulnar nerve neurotization. E, F and G: Clinical result 6 months after the neurotization.

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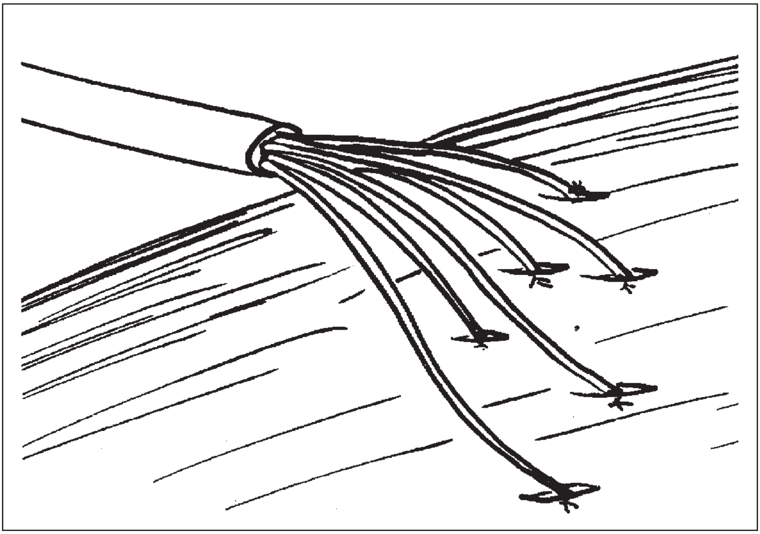

Fig. 2.4. Direct muscular neurotization. Nerve fascicules are placed, spread over the muscle surface, with single stitches in small slits made in the muscle.

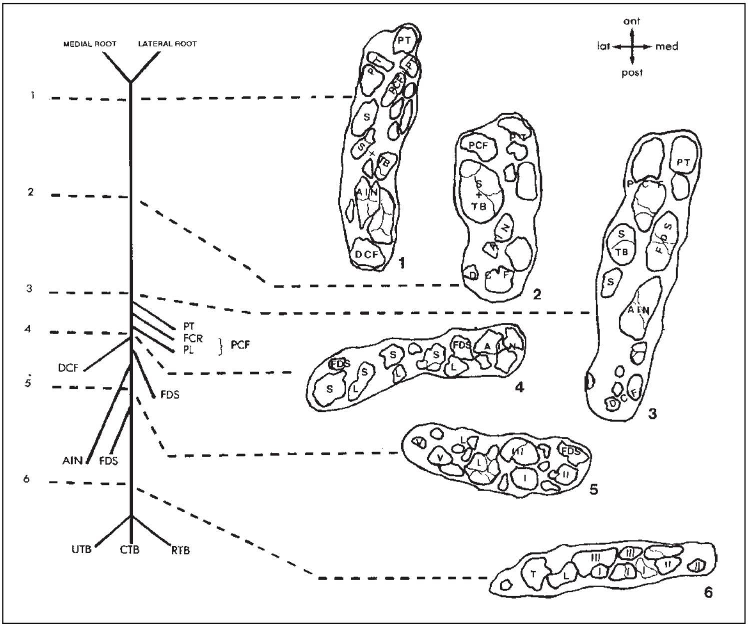

Fig. 2.5. Maps of the median nerve at different levels.

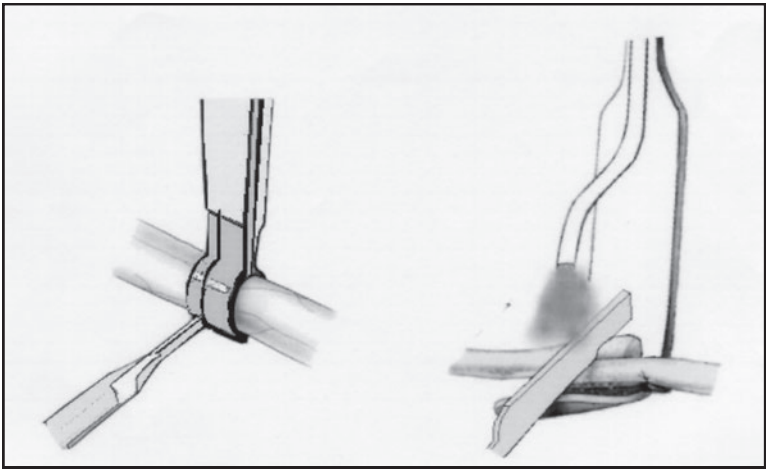

Fig. 2.6. Nerve trimming. A: Meyer's instrument (guillotine type). B: de Medinaceli instrument for freezing and trimming

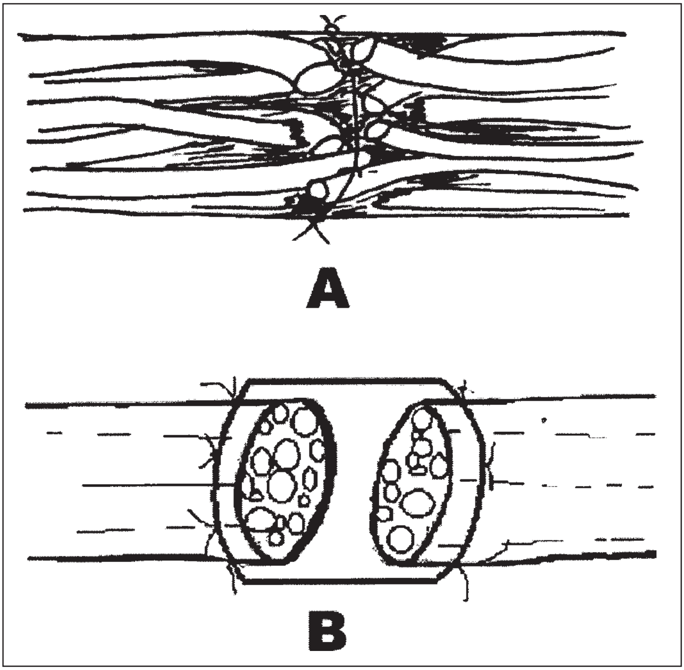

Fig. 2.7. A: Mismatching of the single fascicules is possible inside an epineural suture. B: Tubes allow spontaneous orientation of regenerating axons.

2

Site of Lesion

The site of the lesion is very important both for the level of the injury and the anatomical district.

Level

The more proximal the lesion, the more difficult it will be to obtain a good functional result as fiber mixing increases at the proximal levels. The nerve becomes simpler distally as it leaves its collateral motor or sensory branches. Distally, the terminal branches organize to reach their final targets, so, the best results can be obtained at a distal level. Therefore, from a prognostic point of view, we may divide the possible lesion sites into 4 groups with inferior results from proximal to distal: plexus—nerve trunks—well defined peripheral nerves—terminal branches.

Anatomic District

This factor is important when considering the possibility of performing a direct suture or using grafts to repair a nerve gap without inducing tension on the nerve stumps themselves. Tension is one of the main elements which influences the quality of nerve repair and will be discussed in detail further on. Several authors suggest that a direct suture can be performed if the nerve gap is between 0.5 and 2 cm. The anatomical site is important, in as much as it influences the possibility to mobilize the nerve stumps: 0.5 cm gaps need a graft at finger level, while 2 cm gaps may be solved by a suture at the axilla for as it is possible to approximate the stumps. At the elbow level, an injured ulnar nerve may be directly sutured rerouting it anteriorly, even in the presence of a 2 cm gap.

Timing

Several studies showed that primary nerve repairs give better clinical results than delayed ones.[24,25] However, experimentally, nerve regeneration is improved if the repair follows the lesion at 3-4 weeks. Therefore, some authors[25] prefer waiting 20-60 days before performing nerve reconstruction. Primary repair is, however, always to be preferred in neat, isolated and distal lesions or in replantation surgery.

The time interval between injury and nerve repair is a critical factor and has been investigated at length. Distal to the lesion, irreversible changes take place in both the nerve and the distal end organs (muscles and sensory receptors). In the nerve, after Wallerian degeneration has brought about its well known changes, as time goes by Schwann cells gradually disappear, the nerve trunk becomes fibrous and axonal regeneration is difficult. Muscular fibers, if denervated for a long period, degenerate and, even if nerve ingrowth is later induced, their function is jeopardized. The type of muscle involved is also important: the small intrinsic muscles of the hand need a quick reinnervation for an optimal recovery. The conclusion may then be that 12-18 months after a nerve lesion any attempt at surgical repair, more often than not, leads to failure.

Technical Factors

The main technical factor that dramatically improved nerve repair and the clinical results is that of the introduction of magnification. Nowadays, loops and the microscope are mandatory in this kind of surgery.

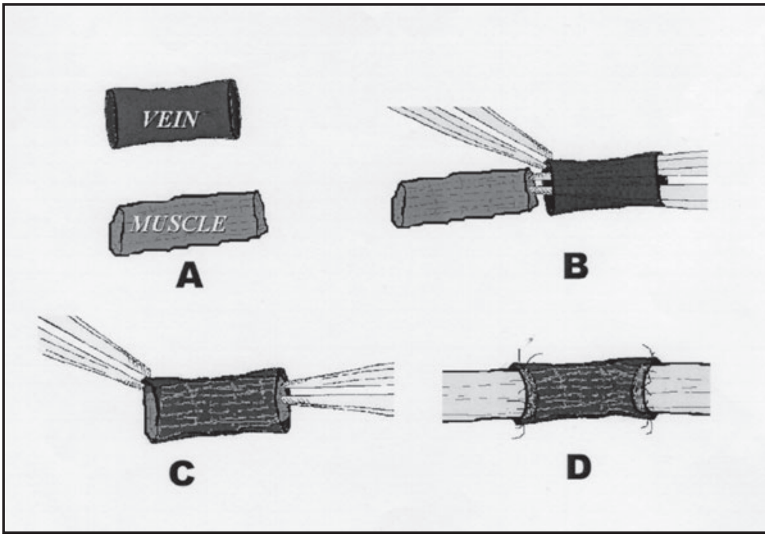

Fig. 2.8. Combined muscle-vein conduit. A, B and C: Single steps of tube preparation. D: final reconstruction (nerve stumps are inserted 2-3 mm into the vein).

Tension in nerve repair is a critical factor. Millesi has well emphasized that, with tension, fibrous tissue develops obliterating axonal regeneration.[26] This finding applied to the systematic use of grafts, even in small gaps, indicates the importance of preventing tension and fibrous reaction. However, Merle reminds us that sutures are to be preferred to grafts if tension may be avoided with small “tricks” (slight joint flexion, etc.) for results superior to grafting, (regenerating axons have to overcome a single barrier instead of two suture lines).[25]

Orientation of fascicles in sutures or grafts contributes significantly to the final result. Misdirection could lead the regenerating axons to a mistaken final target. Several “tricks” may be used to correctly orient the fascicles. Epineurial vessels must be observed. The design of a nerve map (Fig. 2.5) helps the surgeon to face the nerve stumps: this is easier with the use of methylene blue to better recognize fascicle grouping. Intraoperative electrical stimulation of the nerve is also often useful. Histochemistry is used by some authors to distinguish motor from sensory components in frozen specimens; however, this is a difficult technique and lengthens operative time.[27]

Nerve stump *trimming* is another important factor. Meyer[28] developed personal instruments (guillotine type) to obtain a neat cut (Fig. 2.6A). DeMedinaceli[29] pointed out the importance of liquid outflow from the cut ends of the trimmed nerve: then he developed a technique which consists in the cutting of the previously frozen nerve stumps and then suturing them with the help of a mini reabsorbable plate to transfer tension far from the suture site (Fig. 2.6B). We are of the opinion that a clean cut obtained with a microsurgical blade is sufficient.

2

As to *suture materials*, nerve sutures may be performed by means of traditional threads or alternative techniques such as fibrin glue or laser nerve welding. Generally, microsurgeons still prefer traditional monofilament threads (nylon, polypropylene) because of their biocompatibility and for absence of local inflammatory reaction. Furthermore, the use of single stitches give the surgeon the opportunity to coapt opposing fascicles in every single case. Over the years there has been much discussion as to the superiority of perineurial sutures versus epineurial ones (Fig. 2.1A-2.1B) and the question is still under debate. Millesi supports the idea that epineurial tissue may cause greater fibrosis at the suture site and fascicle facing is easier when epineurium is removed and single groups of fascicles are sutured by means of their perineurium. Other authors suggest that loose epineurial sutures give less fibrotic reaction and better clinical results even if a perfect coaptation of the single fascicles is impossible inside the nerve (Fig. 2.7A).[10] Experimental research has shown no difference between the two different techniques.[30] Lundborg[9] says that, at proximal levels, where separate fascicles contain a mixture of fibers with different tasks, there is no reason to put any effort into coapting separate fascicular units by perineurial stitches; on the other hand, at distal levels where branches are well defined, the fascicular suture technique might have a place. We are of the opinion that a combination of epineurial and perineurial stitches may often have a place in suture techniques: perineurial stitches are used to secure defined fascicular groups in position and part of epineurial tissue is preserved and sutured to assure the strength and main orientation of the whole nerve. In the case of interfascicular nerve grafting we prefer the use of epiperinurial stitches (perineurium of the lesioned nerve fascicles and epineurium of the sural grafts) as suggested by Millesi.

Fibrin glue, composed essentially of two components (human fibrinogen + apoproptin, which are fibrinolytic inhibitors, and thrombin, that activates fibrinogen), makes for an easier and faster suture. It has been used systematically by some authors especially for nerve grafting.[31] The glue assembles sural nerve cables, and is also used for the suture site, thus saving time and giving similar clinical results to the ones reported with traditional sutures (Fig. 2.1D).

Laser welding avoids the introduction of foreign materials into the repair site and is based on denaturation and renaturation processes caused in proteins by thermal heating by the laser beam. Although some authors claim that laser repair leads to inferior scar formation,[32] despite the advantages, laser coaptation lacks tensile strength.

Scar formation is another factor which has to be technically contrasted; as already stated, tension must be avoided while reconstructing peripheral nerve lesions and nerve sutures must be surrounded by well vascularized soft tissues. Nerve regeneration may not be present at times even after a good surgical reconstruction as a result of scar formation. If the surgeon is in doubt from no further advancement of the Tinel sign and lack of muscle recovery, neurolysis must be carried out. During the surgical revision we may check the suture lines and an external neurolysis may be performed; deep internal neurolysis is not useful and may devascularize the regenerating fibers. New scar formation may also be prevented by local or microsurgical flaps or even by barrier substances (Adcon TN).

Biomolecular Factors

Several morphological and biochemical changes occur in the nerve cell body following the transection of a nerve trunk. This reflects the changes in the synthesis of cytoskeletal elements which are required to replace the loss of axon substance. At the site of axonal injury, sprouts start to grow distally and several biomolecular factors are involved to support the outgrowth and direction of axoplasm.

These biomolecular factors could be subdivided into three major groups: neurotrophic factors, neurotropic factors and neurite promoting factors (NPF).[9,33]

Neurotrophic factors are endogenous soluble proteins influencing survival, development and morphological plasticity of nerve cells ("neurotrophism"). These factors are synthesized in neurons, muscle, glands and are classified on the basis of their receptors: neurotrophins (NGF, BDNF, NT-3, NT-4/5), neuropoietic cytokines (CNTF, IL-6), fibroblast growth factors (aFGF, bFGF,FGF-5, FGF-6), insulin gene family (ITF-I, IGF-II, insulin) and others (LIF, EGF, TGFα, TGFβ, CDNF). The prototype for a trophic factor, the nerve growth factor (NGF),[3] binds to its receptors, is internalized in vesicles and then transported, by retrograde axonal transport, to the cell body, where it exerts its action.

Neurotropic factors influence the axonal growth direction by exerting an attraction at a distance ("neurotropism"). These factors, delivered by the distal nerve segment, create a concentration gradient. It is not strictly correct to separate "trophic" and "tropic factors" completely, and it has been suggested to use the terms "trophic" and "tropic influence": factors secreted by non-neuronal cells in a distal nerve segment after an injury which normally have a trophic influence that may act like tropic factors, thereby exerting an attraction at a distance, influencing also the axonal growth direction.

Neurite promoting factors (NPF) are substances promoting the growth cone formation. Laminin and fibronectin are examples of substances included in the extracellular matrix wile N-CAM and L1 are examples of cell surface molecules providing adequate adhesions for the advancing sprouts.

The better understanding of these biological factors involved in the nerve regeneration process guided researchers in their efforts to improve nerve repair. Indeed much has been done to overcome problems connected with the correct orientation of fascicles not only in direct sutures but also with regard to nerve repair in the case of loss of nerve substance. These two problems have both been faced by the development of the so-called tubulization techniques.

The tubulization principle represents a biological approach to a nerve injury, in which the role of the surgeon is limited and special emphasis is given to the role of intrinsic healing capacities of the nerve tissue itself.

To solve the problem of misdirection of the regenerating fibres leading to inappropriate distal reinervation, Lundborg suggested to encase both ends of a transected nerve in a silicon tube, leaving a short gap in between (3-5 mm), allowing the accumulation of these biological factors inside the tube (Fig. 2.7A, 2.7B). The early results from a prospective, randomised, clinical study showed that tube repair gives at least as good prerequisites for recovery of nerve function as conventional repair technique.[34]

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As for the repair of peripheral nerve defects, it is usually accomplished using the aforementioned fascicular grafting technique. This provides continuity of the stumps, with minimal or no tension, and supports axonal regeneration by means of the Schwann cells and/or the inner surface of the Schwann cell columns, protecting against surrounding scar tissue formation. However, even if this technique usually provides good functional results, there are some problems in its application: it does require an extra surgical procedure that may lead to damage created by the withdrawal of a healthy nerve (surgical incisions in sound areas, sensory residual deficits). Furthermore, graft material is limited (in terms of length) especially in cases requiring the repair of extensive lesions, such as brachial plexus lesions.

Many biological and synthetic materials have been tested to bridge a peripheral loss of substance: arteries, veins, mesothelial chambers, predegenerated or fresh skeletal muscle, empty artificial tubes, resorbable or not, tubes filled with growth factors and/or Schwann cells. Unfortunately, all of these "tubes" are useful for short distances only. In particular, vein or other empty tubes collapse in gaps over 1-2 cm and axon loss may occur in muscle grafts. Therefore, a major limitation of tubulization grafting techniques is the fact that they can be used only for short distances (1-2 cm).

Since 1993, we have carried out some experimental and clinical trials on the use of "tubes" made from a vein filled with fresh skeletal muscle (Fig. 2.8A, 2.8B, 2.8C, 2.8D). This biological tubulization combines two elements that have been previously shown to have limitations in their separate application for nerve repair. The vein guides regeneration and the muscle prevents vein collapse. Moreover, the muscle provides an adequate "adhesion" for the advancing sprouts by means of neurite promoting factors present in its basal lamina (laminin and fibronectin) mimicking the Schwann cell adhesion role. Many studies have been carried out on the possibility of using the muscle basal lamina as scaffold for nerve regeneration.[35] Moreover, extracts of fresh skeletal muscle have been shown to increase neurite outgrowth.[36] We demonstrated that vein conduits, filled with fresh skeletal muscle, provide morphological results in rats similar to traditional nerve grafts, in cases with a substance loss of up to 3 cm.[37] We have applied this technique in our cases since 1993 with good functional results for both sensory and mixed nerves up to 5-6 cm.[38]

Therefore, we put foreword the hypothesis that the support of the basal lamina, and chemiotrophic and chemiotropic substances originating from the distal stump, do indeed reach the regenerating axons and correctly guide them to their final target tissue.[39] This may well explain our good clinical results, whilst traditional nerve grafting techniques somehow forces the orientation of regenerating axons.

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Vein Wrapping for the Treatment of Recurrent Entrapment Neuropathies

Sokratis E. Varitimidis, Dean G. Sotereanos

Introduction

Entrapment neuropathies are common entities in surgery of the upper extremity. The gold standard for operative treatment in this condition is surgical decompression of the entrapped nerve. Releasing the transverse ligament at the volar surface of the wrist for carpal tunnel syndrome and decompressing the ulnar nerve at the elbow for cubital tunnel are generally procedures with very satisfactory outcome. Despite the high success rates reported in the literature, recurrence of the compression is not uncommon.

If primary decompression was adequate, the reasons for failure include cicatrix formation and adhesion of the nerve with the surrounding tissue.

Management of recurrent entrapment neuropathies is difficult and controversial. Repeated nerve decompression, alone or accompanied by external or internal neurolysis, does not always relieve symptoms. Reports in the literature describe supplementary procedures in the revision setting such as the covering of nerve with muscle flap, fat flap, fascia flap, or even vascularized omentum.

The outcome of these procedures is generally unpredictable, and some techniques are associated with concomitant morbidity.

Masear et al[1] reported the technique of using venous wrapping of nerves to prevent scarring for severe and recurrent nerve compression. In their clinical study, both autograft and allograft of vein were used to wrap the median nerve after decompression. Their results showed marked improvement in pain. A remarkable absence of scarring around the vein graft was noticed during surgical exploration for secondary reconstruction in three patients. In 1991, Gould[2] also described this technique for the treatment of the painful injured nerve in continuity. Koman et al[3] evaluated the symptomatic and functional assessment of allograft umbilical vein wrapping for dystrophic median nerve dysfunction. Their encouraging results showed that wrapping the nerve with a vein graft following decompression can improve recovery of nerve function and be beneficial to patients with severe recurrent nerve compression.

Since 1993, we studied the effect of vein graft wrapping around peripheral nerves. Our project included both experimental and clinical studies.[4]

The experimental study was planned in two steps. The first part was to wrap a vein graft on normal sciatic nerves using a rat model. In this part we assessed the

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effect of vein wrapping on normal nerves using electrophysiologic and histologic evaluation. In the second part of the experimental study we wrapped a vein graft around sciatic nerves in which previously we created compression and scarring. The sciatic nerve was later evaluated functionally and by electrophysiologic and histologic examinations. The results were very encouraging. Function of the sciatic nerve and electrophysiologic studies were improved and histologic examination showed that no scar tissue developed between the epineurium of the wrapped sciatic nerve and the intimal surface of the vein.[5]

Encouraged by the results of this study, we applied the vein wrapping technique to patients with recurrent compressive neuropathy of the median and ulnar nerves.

Indications for the Technique

Candidates for this procedure are patients with recurrent carpal or cubital tunnel syndrome that failed at least two previous releases. Before surgery a history and physical examination must be performed. The principal complaint of the patient must be clearly defined. It must be noted if the patient had any relief of symptoms after the first operation to indicate scarring as the cause of recurrent symptoms. Physical examination should include measurement of two-point discrimination (TPD), range of motion, grip strength, Tinel's sign, and Phalen's sign. An electromyography (EMG) test is recommended to note worsening or improvement relative to a previous study. A detailed set of indications are

a. patients who have undergone at least two carpal tunnel or cubital tunnel releases and who complain of recurrent symptoms;
b. the symptoms and physical examination findings improved for a short period of time and then recurred or were exacerbated after the previous carpal tunnel release; and
c. patients with scarring of the median nerve or neuroma formation. A contraindication for the technique is chronic lower-extremity venous insufficiency.

Surgical Technique

The procedure is done under general anesthesia because two operating fields (one at the upper and one in the lower extremity) exist concomitantly. The standard approach used for the primary operation is used also for the revision surgery with the difference that the incision needs to be extended both proximally and distally because the compressed nerve must be exposed first in an unscarred tissue environment. The median or ulnar nerve is identified and separated from the surrounding scar tissue. This dissection is done under 3.5-loupe magnification. With the use of an operating microscope for better magnification and visualization internal neurolysis is performed if severe scarring and compression extends into the fascicles. The nerve fascicles are freed from the scar tissue and unobstructed nerve excursion is obtained.

The greater saphenous vein is harvested from the ipsilateral or the contralateral lower extremity. The incision is made longitudinally 1 cm anterior to medial malleolus. Usually a vein length of 25-30 cm is needed and the incision is made accordingly. The required length is three to four times the length of the nerve segment that is going to be wrapped. Care is taken to avoid injury of small nerves and other vein branches. After the saphenous vein is harvested, it is incised and opened longitudinally (Fig. 3.1). One of the ends of the vein graft is tacked distal to the scarred portion of the nerve, on a tissue that is not mobile, with the intima against the nerve, using a 7-0 or 8-0 nylon stitch. The wrapping proceeds circumferentially as described by Masear at al.[1] from distal to proximal (Figs. 3.2 and 3.3). After each complete circle of the vein on the nerve the vein is stabilized with a loose 7-0 or 8-0 nylon stitch to the adjacent ring of vein (Fig. 3.4). The other end of the vein graft is tacked proximal to the scarred segment of the nerve, on unscarred epineurium (Fig. 3.5). It is important to cover completely the scarred segment of the nerve because this may cause scarring again as Masear and Colgin[6] reported in their series. 3

Postoperatively, for the median nerve, the wrist is immobilized for one week, in slight extension. For vein wrapping of the ulnar nerve the elbow is not immobilized.

Complications

Lower extremity swelling secondary to saphenous vein harvesting may occur in a small portion of patients that undergo this procedure. Usually this resolves at 3-4 months postoperatively.

Discussion

Chronic nerve compression is one of the most common clinical phenomena in the peripheral nervous system. Surgical decompression of entrapped peripheral nerves is generally efficacious. However, a significant number of patients do not experience good long-term results with this treatment, and the socioeconomic impact is enormous.

Multiple attempts of surgical releases can create more scar tissue which develops and further compresses the nerve. The epineural surface of the nerve is surrounded by scar tissue and stressed by strenuous work or a new injury. The result is a chronic neuropathy, called a "traction neuropathy" and the optimal treatment may be a combination of procedures. Mobilization of the nerve followed by internal neurolysis cannot alleviate these problems, due to recurrent scar. Most authors agree that soft tissue coverage is necessary to prevent this phenomenon, and several options have been suggested for this purpose. For recurrent carpal tunnel syndrome the hypothenar fat pad flap can produce good results and is uncomplicated in most cases. Pedicle or free flaps, including the groin flap, lateral arm flap, posterior interosseous flap, provide excellent protection of the nerve, but the technique is complex and the results not always satisfying. Small local flaps such as the abductor digiti minimi, the palmaris brevis, the pronator quadratus and lumbricalis also have been used. However the dissection of these flaps is not always easy, and skin closing problems may occur. Also the coverage provided by these local flaps is often inadequate. Use of implanted peripheral nerve stimulators has been suggested to relieve pain resulting from compressed of injured peripheral nerves, but failures have been reported in many cases because of complications such as nerve injuries, skin problems, and early formation of scar tissue due to silicone.

Masear et al[1] were the first to report the successful use of a vein graft for treatment of recurrent compressive neuropathy. Gould[2] and Koman et al[3] have also shown that the vein graft wrapping technique can improve the recovery of nerve function,

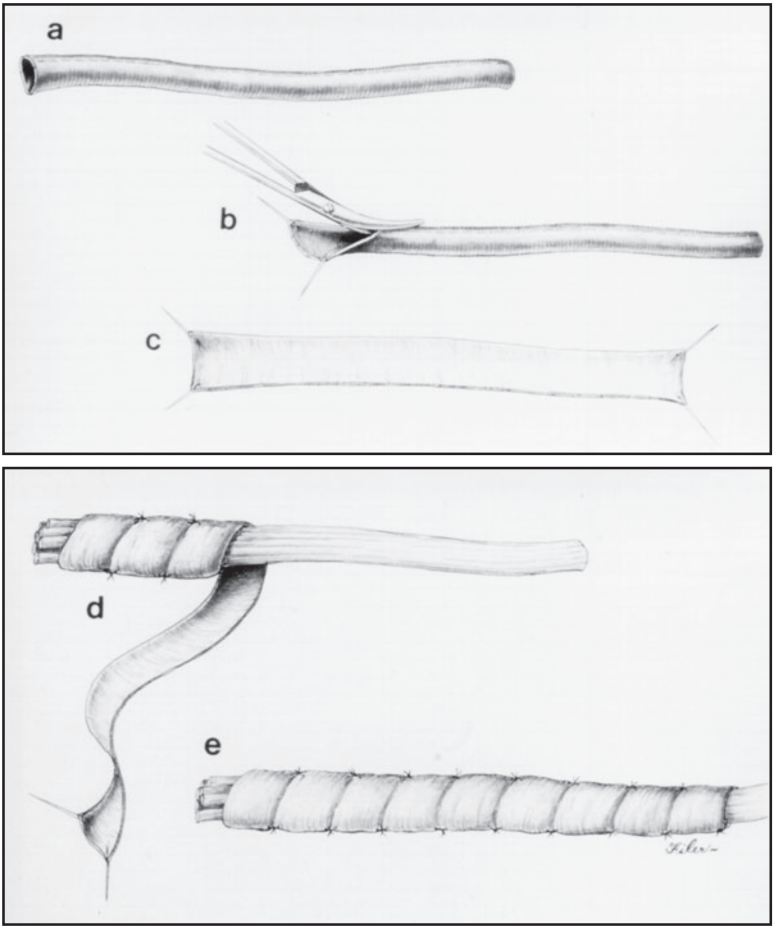

Fig. 3.1. A and 1B. Artist's drawing showing the technique used for vein wrapping of scarred nerves. a: The saphenous vein is harvested from the ipsilateral or contralateral leg, b: is split longitudinally, and c: opened to form a rectangular. d: The saphenous vein is wrapped around the scarred portion of the nerve in a spiral pattern with its intima on the surface of the nerve. Each ring of the nerve is tacked to the adjacent rings with a 7-0 or 8-0 nylon stitch. e: The entire scarred portion of the nerve is covered with the saphenous vein.

in patients with recurrent nerve compression. Malizos et al[7] used vein conduits to bridge small defects in sensory nerves and in covering the stump of sensory nerves after neuroma excision with satisfactory results in pain relief.

Our experimental studies, as well as other studies, have shown that wrapping a compressed nerve with an autologous graft is an excellent option for treatment of recurrent neuropathy. However, the mechanism of its effect is still uncertain. Based

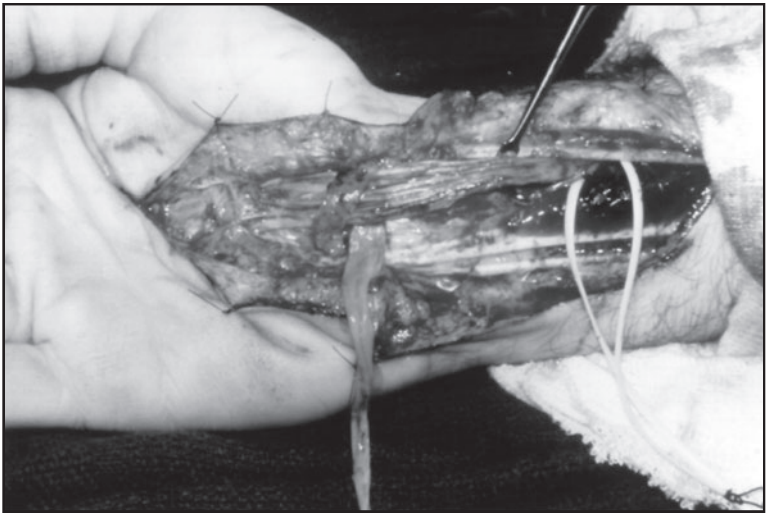

Fig. 3.2. The median nerve has been exposed at the wrist, and cleaned of scar tissue. Internal neurolysis has been performed and the saphenous vein is tacked distally. The intimal surface of the vein is facing the surface of the nerve.

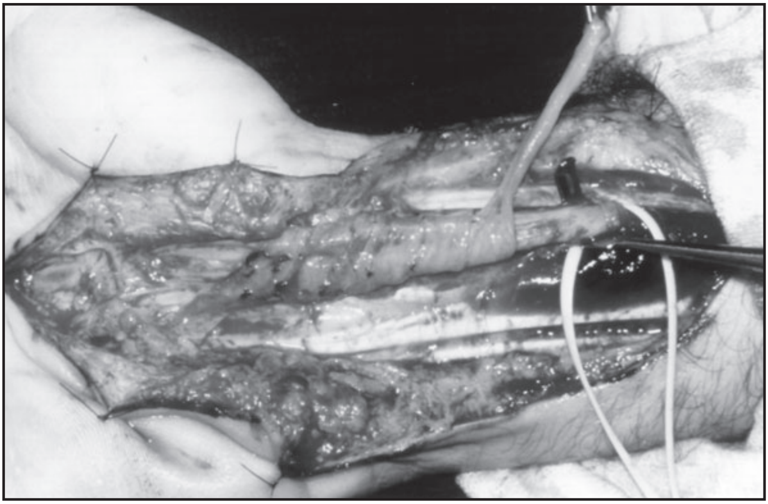

Fig. 3.3. The wrapping of the nerve with the saphenous vein proceeds circumferentially according to the technique described by Masear et al (1990).

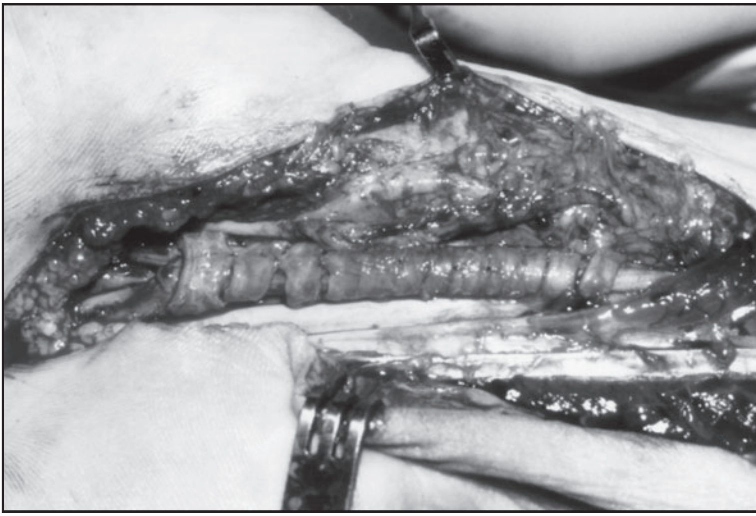

Fig. 3.4. The saphenous vein covers the entire portion of the nerve where internal neurolysis has been performed.

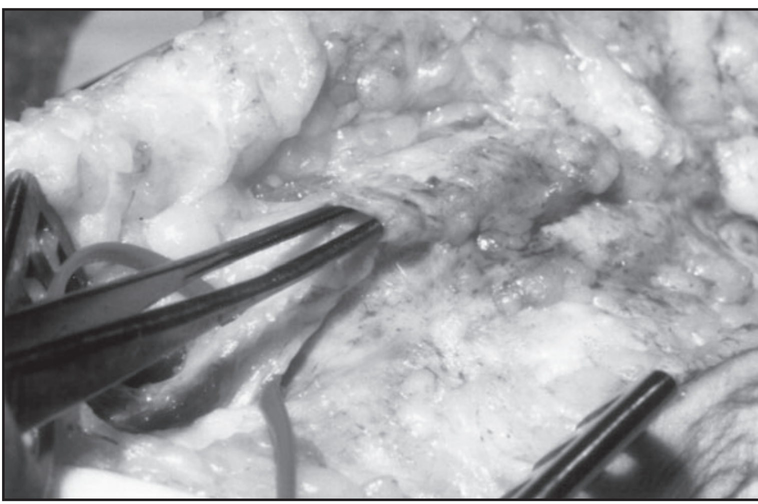

Fig. 3.5. This patient underwent an exploration for a neuroma of the medial antebrachial cutaneous nerve two years after vein wrapping of the ulnar nerve at the cubital tunnel. There was no scar tissue between the intima of the vein and the surface of the ulnar nerve. A forceps could easily enter the space between the wrapping vein and the wrapped nerve.

on etiology, and the pathophysiology of recurrent nerve compression, we believe that the procedure works by protecting the peripheral nerve from surrounding scar tissue, thereby preventing adhesion between the nerve epineurium and the surrounding tissue. In addition, the formation of scar tissue within the peripheral nerve trunk is minimized after vein wrapping, possibly, due to properties of endothelial cells of the intimal layer of the vein.

Endothelial cells prevent the adhesion of tissue or blood cells to the inner surface of the vessel in vivo. Perhaps the vein graft also functions in a similar fashion, preventing adhesion and scar tissue formation between the periphery and the nerve. In addition, the autogenous vein graft with this smooth inner surface should improve the gliding function of the nerve trunk during motion of the relevant joint, avoiding the possible damage induced by gliding friction of the trunk and/or "spot welding" of the nerve to scar tissue with subsequent traction neuropathy.

Pain, which is often associated with recurrent compressive neuropathies, subsides significantly after vein wrapping. Sensation and two-point discrimination in the median nerve distribution in the hand are also improved in most cases. Follow-up electromyographic studies in most patients revealed improved nerve conduction velocity and amplitude.

The use of autogenous vein graft wrapping as a supplementary technique to treat chronic nerve compression has many advantages. It is a simple technique that causes minimal complications in the donor area. In addition, the donor is readily available, with easy harvesting. Based on the results that we observed, we believe that vein wrapping as a treatment option for refractory chronic neuropathy is an excellent adjuvant procedure.

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Upper Extremity Replantation

John S. Taras

The advent of microsurgical techniques to extremity trauma has enhanced the surgeon's ability to reconstruct amputating injuries by replantation. As more surgeons are now trained in microsurgical techniques, replantation is routinely offered at many trauma centers. Viability rates higher than 80% have been reported in several published series.[1-15] Replantation is defined as the reattachment of an extremity part that has been completely cut off and reconnection of the damaged vascular structures. Revascularization is the repair of a partially amputated extremity part with impaired circulation.

As we gain technical experience in restoring extremity function through replantation, we gain a better understanding of the factors influencing the decision to replant or revascularize an amputated part. Reasonable expectations should compel the decision to replant or revascularize an injured extremity or to amputate and fit a prosthetic. Every case must be analyzed individually, taking into consideration the circumstances of the trauma and the patient's needs and desires.[16-18]

Indications for Replantation

The level and extent of injury are the most important determinants in the decision to proceed with replantation. In replantation, observation of functional results at different anatomical levels guides our indications. Good candidates for replantation include patients with amputating injuries of the thumb, multiple digits, hand, and wrist. When the amputation occurs through the forearm, at the elbow, or at the arm, only sharp or moderately avulsed injuries are considered favorable candidates. Patients having guillotine-type amputations are the best candidates for replantation because of the limited zone of injury, but this mechanism of injury is also the least common. Most amputations occur by crushing or avulsion, which increases the zone of damaged tissues, makes the surgical repair more difficult, and lowers viability.[19-21] The extent of the zone of injury generally determines whether a part can be replanted.

In general, thumb replantation should be attempted when it is technically possible.[22-26] The function of a replanted thumb with return of at least protective sensation is superior to that of a prosthesis for tasks requiring fine dexterity. The functional results improve with more distal thumb replantations (Figs. 4.1 and 4.2).

Traumas involving amputation of multiple digits are good candidates for replantation (Fig. 4.3). It is often the case that surgeons can replant only the least damaged parts. Digits can be transferred from their natural position to a more functional position or to a more suitable stump.[27] When possible, it is more appropriate to

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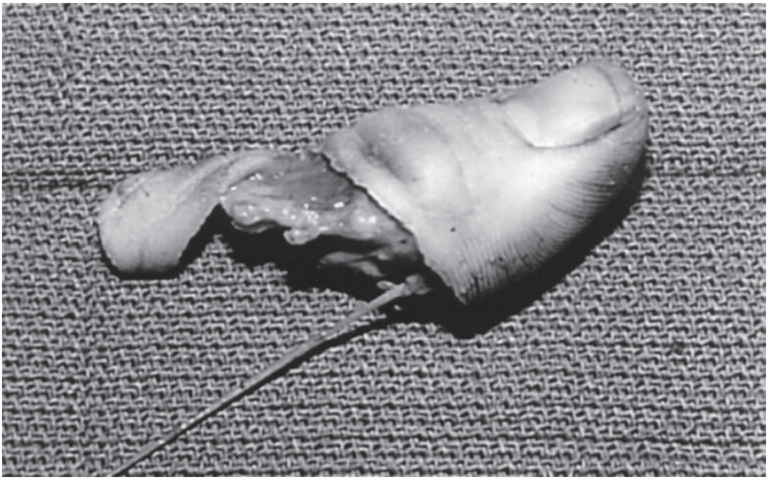

Fig. 4.1. Thumb replantation through interphalangeal (IP) joint with good functional and cosmetic results.

Fig. 4.2. Thumb replantation at metacarpophalangeal joint (MCP) level permits fine dextrous tasks difficult to perform with a nontactile prosthesis.

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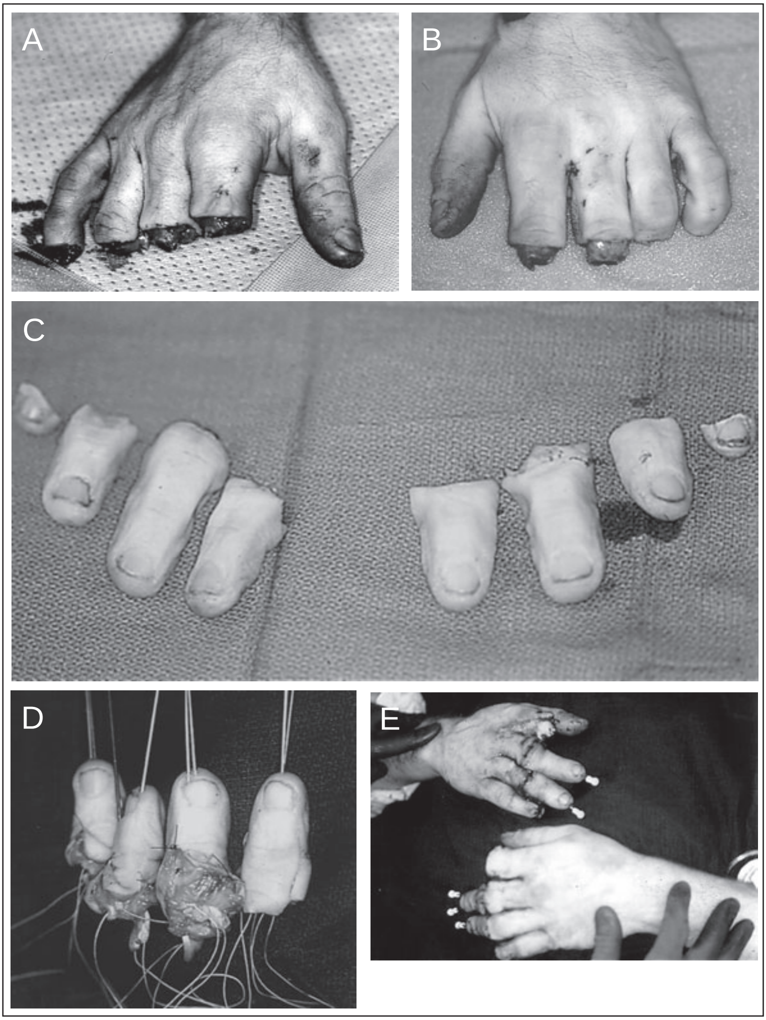

Fig. 4.3. A,B,C, Day of injury photographs of 8 finger amputations. D, Distal parts are dissected and prepared for replantation before the patient enters the operating room. E, Appearance of the digits just after replantation with the distal index amputations replanted onto the long finger stumps to preserve central digital function.

replant the central, middle and ring digits than the index and little fingers, which are border digits.

Replantation of injuries through the palm, wrist, and distal forearm generally provides better function than can be achieved with a prosthesis.[28] Recovery of

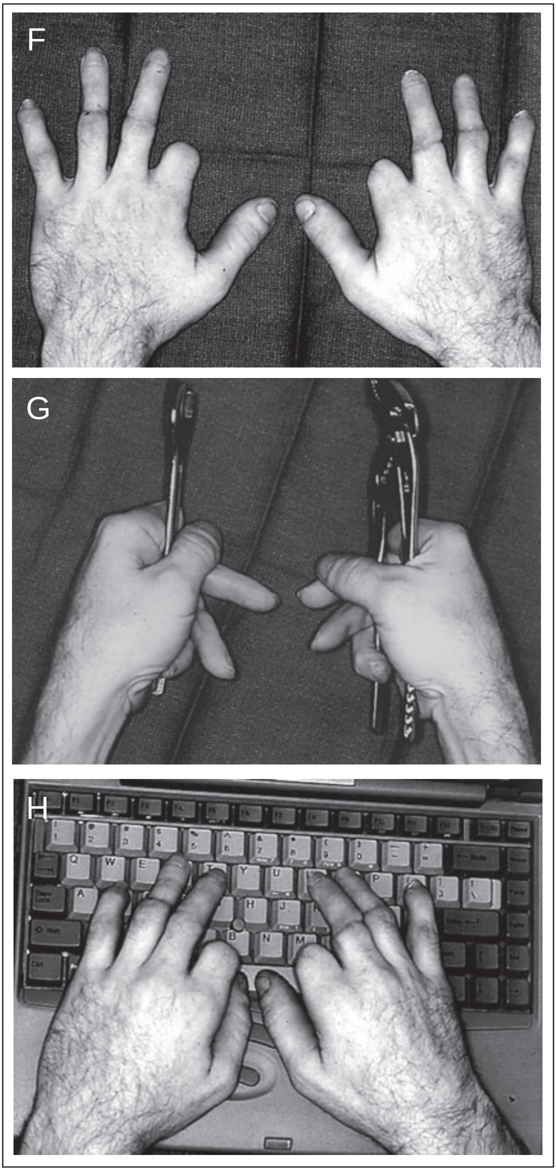

Fig. 4.3, cont. F,G,H, Good cosmetic appearance, gross grasping, and fine dextrous function allowed this man to return to his former job, which would not have been possible with revision amputations.

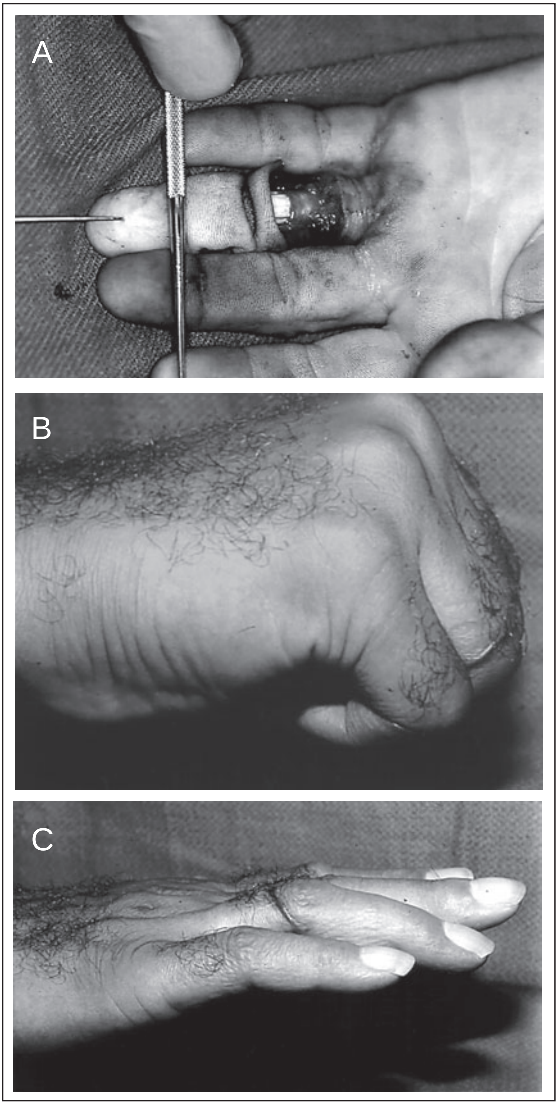

Fig. 4.4. A,B,C, Urbaniak Class II ring avulsion with near normal restoration of range of motion after revascularization.

protective sensation is typical, and although intrinsic muscle function recovers poorly, the extrinsic muscles provide useful grasp.

Replanted digits distal to the superficialis insertion generally function well and are considered cosmetically preferable to an amputation stump or prosthesis.[29-35]

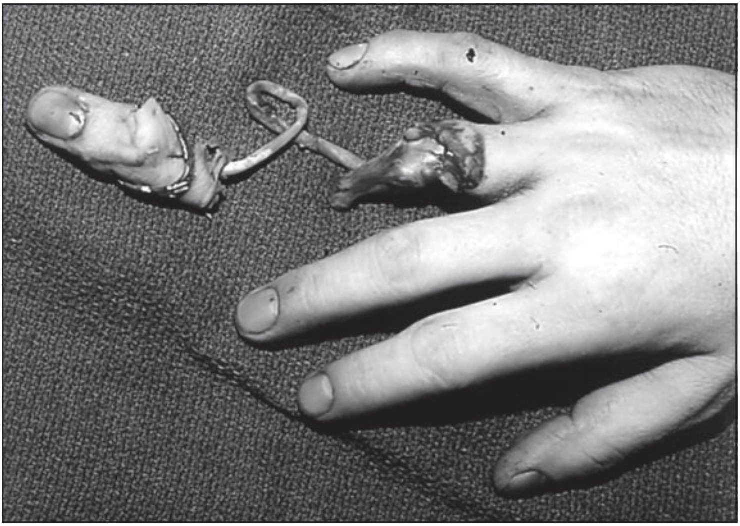

Fig. 4.5. Urbaniak Class III ring avulsion injuries function poorly after replantation. This case was treated with primary amputation.

Amputations distal to the distal interphalangeal joint (DIP) can be replanted successfully if at least 4 mm of dorsal skin proximal to the nail fold remain where dorsal veins can be reapproximated. Injuries through the nail bed generally are not considered favorable for replantation. Patients with single digit amputations through zone II or proximal to the superficialis insertion can be expected to have poor interphalangeal motion when replanted and are considered poor candidates.

Ring avulsion injuries as classified by Urbaniak[36] are divided into three categories:

1. Class I—circulation adequate;
2. Class II—circulation inadequate with preservation of skeletal and tendon structure (Fig. 4.4); and
3. Class III—complete degloving or amputation (Fig. 4.5). Class II ring avulsions are good candidates for vascular repair but class III ring avulsions are not.

Major limb replantation at the level of the proximal forearm, through the elbow, and at the humeral level must be undertaken with caution. At the outset, surgeons must understand only limited function may be restored. This realization must be weighed against potential complications when making the decision to undertake replantation.[28,37-39]

The patient's age factors into the decision to replant an amputated part. Replantation of almost any amputated part generally is recommended for healthy children. Epiphyseal growth continues after replantation, sensibility is usually restored better than adults, and functional results are generally good.[40-49] (Fig. 4.6). Advanced age increases the potential morbidity of the procedure because chronic medical conditions are more prevalent in older adults. As age increases, so also do potential complications.

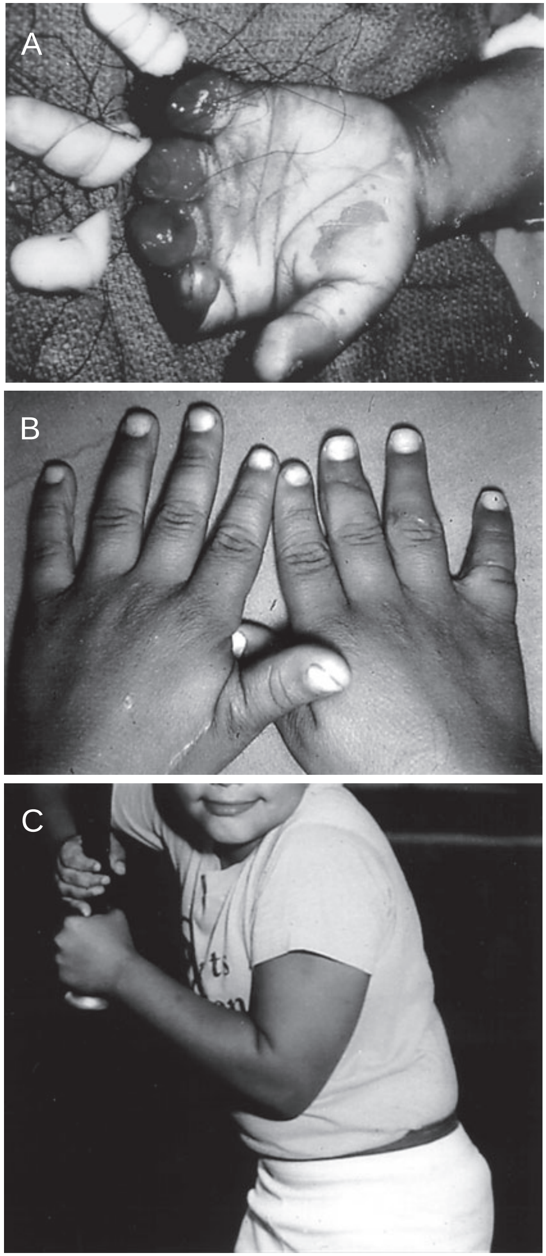

Fig. 4.6. This case of pediatric multiple digit replantation from the Duke University series (References 45 and 46) illustrates the generally good results achieved when replantation is successful.

Ischemic time of an amputated part is an important consideration for replantation. Although there are no strict criteria defining maximum ischemic time for replantation, a warm ischemic time longer than 6 hours for an amputation proximal to the carpus or longer than 12 hours for the digits generally precludes consideration of replantation. It is possible to extend the ischemic time with cooling of the amputated part; however, if the cold ischemic time is longer than 12 hours for a proximal amputation, replantation is not generally performed.

Patients with severely mangled amputated parts or proximal stumps are poor candidates for replantation[50] (Fig. 4.7). In certain cases in which the proximal stump is grossly contaminated, and multiple debridements or further reconstruction are required before replantation, it is possible to "park" an amputated part by temporarily coupling the arterial and venous connections in a location distal to the amputation site.[51-52] Other contraindications to replantation include concomitant severe trauma or chronic illness, advanced arteriosclerotic vessel changes, and mental instability.

Preoperative Care

The initial management of a patient with an amputating injury follows general trauma guidelines. Care must be taken to evaluate other injuries, to assess the general medical condition of the patient, and to care for the injured extremity. Control of bleeding is an immediate priority. Direct pressure on the amputation stump is the first step in stopping hemorrhage. When this is unsuccessful, pneumatic occlusion of blood flow proximal to the injury can be used to allow emergent exploration of the major vessels. Care should be taken not to blindly clamp vessels in a bloody field because compression of adjacent major nerves can occur. Replacement of blood and fluid loss is initiated in patients suffering significant loss. Cases of death by exsanguination have occurred during patient transport when insufficient attention was directed toward hemorrhage control and blood replacement.

The amputated part is cared for by first cleansing the part and then cooling it. The part should be wrapped in saline moistened gauze and placed in a plastic bag that is placed on ice. The severed part should not directly contact the ice and should not be frozen. The amputation stump should be cleansed and a bactericidal agent such as iodine solution should be used to apply a moist dressing to the wound.

If transport to a trauma facility is necessary, then instructions to the outlying facility must be outlined clearly. Arrangements are made to secure and set up an operating room so that upon arrival the surgery can be performed promptly. With complete amputation, the amputated part can be dissected while the patient is prepared for surgery. I prefer patients to have general anesthesia because this is the fastest way to initiate surgery at my institution. Alternatively, an indwelling axillary catheter can be placed for a continuous block.[53]

Surgical Management

There is general agreement about the sequence by which to repair damaged structures in replantation, although the level and type of injury may necessitate deviation from the accepted pattern. The operative sequence is:

1. debride;
2. identify and tag vessels and nerves;
3. shorten and stabilize bone;

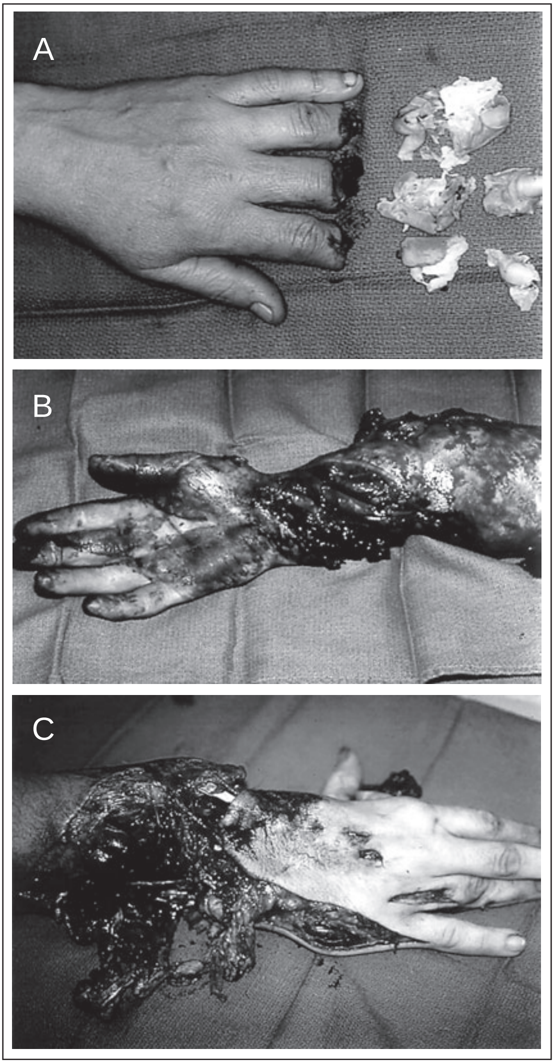

Fig. 4.7. A,B,C, Three examples of severely mangled or crushed injuries which were considered poor candidates for replantation and were treated by primary revision or amputation.

4. repair flexor and extensor tendons;
5. anastomose arteries;
6. repair veins;
7. anastomose veins; and
8. cover skin.

Dissection of the amputated part can proceed ahead of the amputation stump. When this is possible, it is useful to perform as much of the surgery as possible with debridement, tagging of the vessels, bone shortening, placement of tendon sutures, and placement of skeletal fixation while the patient is readied for surgery. A second surgical team can begin dissection of the amputation stump in a similar manner to speed the process.

In the digits, incisions are made longitudinally just dorsal to the midlateral lines. This allows reflection of dorsal and volar flaps to identify all structures. For more proximal injuries incisions provide exposure, but the surgeon must not close these incisions upon completion of the replantation. Thus, incisions are directed away from areas where anastomoses are planned. The initial dissection of the proximal stump is generally performed under tourniquet control to allow the surgeon to accomplish the initial surgical steps faster than can be accomplished in a bloody field.

Bone shortening is accomplished to allow resection of the zone of injury so that the injured structures can be repaired primarily when possible. Bone shortening provides for better skin closure without tension. The amount of bone resection depends on the level of injury. In the digit, it is usually necessary to resect 0.5-1.0 cm of bone. Amputations of the forearm or arm require at least 2-4 cm of bone resection. For phalanges and metacarpals, I prefer using 2 Kirschner wires for fixation. When the proximal stump is grossly contaminated and additional procedures are required before replantation, more rigid fixation devices such as plates and screws are more time-consuming and less amenable to reapplication if additional bone shortening is required after initial hardware placement. Amputation through an interphalangeal joint is generally fixed by fusing the joint in a functional position. For amputations through the carpus, I prefer a proximal row carpectomy stabilized by Kirschner wires. In the forearm and arm, I prefer plate fixation.

The tendon sutures can be placed separately in advance and tied after bone fixation is completed. I prefer to use 3-0 braided polyester with an extra grasping loop to provide a stronger repair, permitting institution of early range of motion in the postoperative period[67] (Fig. 4.8). If the tendon stock is of poor quality, then repair of only one flexor tendon may be preferable; however, repair of all tendons is accomplished whenever possible.

The operating microscope is used to repair arteries, nerves, and veins. Arterial repair is performed after deflation of the pneumatic tourniquet. The damaged ends of the artery are resected back until normal vessel is identified. If segmental damage has occurred, then an interpositional vein graft may be required. Potential donor vessels for grafting include volar or dorsal veins about the wrist, the dorsum of the foot, material from nonreplantable parts, and for larger vessel repairs, the saphenous vein.

Good blood flow should be confirmed from the proximal vessel. If inadequate arterial flow is evident, then several problems may be present and each potential cause should be evaluated. Retracted skin flaps may kink the proximal vessels. A proximal blood clot may block the artery; this can be dislodged by dilation and irrigation or even a small catheter. The vessel may be in spasm. For spasm, local dilating agents such as papaverin, 20% lidocaine, or application of a more proximal sympathetic block can be used to alleviate the spasm. I prefer to inject bupivicaine 0.5% into the wrist to block the median and/or ulnar nerves for digital replants. The patient may require hydration and elevation of the blood pressure.

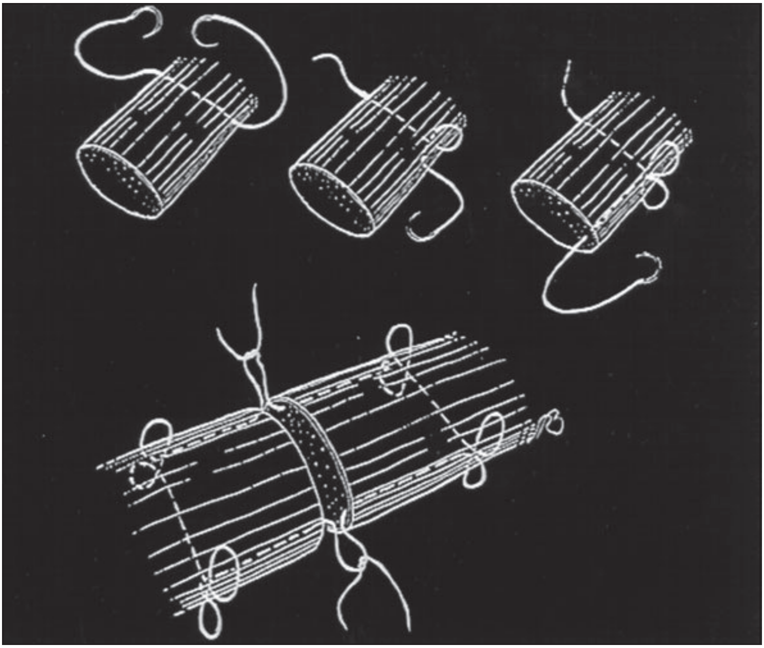

Fig. 4.8. The double-grasping core suture technique

After preparation of the arterial ends, they are irrigated with a dilute heparin solution to prevent adherence of platelets and clotting factors. Vascular repair is then accomplished with interrupted nylon sutures. For distal digital repair, 10-0 Nylon monofilament suture is typically appropriate. Proximal digital repairs usually require 9-0 suture. For amputations at the level of the wrist and proximal, 8-0 suture generally is appropriate. While a minimum of one artery and one vein repair are required for each replant, it is preferable to perform two arterial and three-to-four venous repairs to increase the chances of survival.[54-56] For multiple digital injuries, it may be beneficial to repair one artery in each digit, then repair a vein for each digit to restore circulation before completing the secondary repairs of the other vessels and nerves.

Unique circumstances for each trauma may limit the ability to perform a direct repair of the injured vessels. Arteries can be mobilized and transferred across the digit when a proximal vessel on one side of a digit is of good quality and the distal vessel is of good quality on the other side.

Before initiating the first arterial anastomosis, a bolus of 3000-5000 units of intravenous heparin is administered to prevent clotting at the anastomosis site. A running infusion of 1000 units per hour is then initiated and adjusted throughout the case depending on the patient's degree of bleeding. Heparinization is discontinued at least temporarily if the bleeding is excessive. After the initial assessment of the adequacy of the blood flow through the proximal arteries, the pneumatic tourniquet may be inflated for subsequent vessel repairs when hemorrhage is obscuring the operative field.

Venous repair is usually the most technically challenging part of replantation. An attempt is made to repair two veins for each arterial repair, although this is not always possible. The most common error with vein repair is performing the anastomosis under too much tension. This generally can be avoided with skeletal shortening, but an interpositional vein graft can be used if the veins cannot be mobilized sufficiently to have a tension-free anastomosis. In the digits, the dorsal veins are located in the subdermal plexus. In the amputated part, the collapsed veins may be difficult to locate. After arterial repair with engorgement, their location should be more readily apparent. Some surgeons prefer to perform venous repairs before arterial repairs, finding there is less blood loss and venous repair is easier in a bloodless field. With use of a pneumatic tourniquet during venous repair, this problem can be averted.

The literature describes several techniques that can be used when dorsal venous repair cannot be accomplished readily. These techniques include repair of small and thin-walled volar veins, anastomosis of one distal digital artery to a proximal vein, removal of the nail plate and application of heparin pledges to allow bleeding out of the nail bed, use of leeches, and periodic massage of the digit to enhance venous outflow.[57-59] I rarely rely on these methods, because I find them unreliable.

Primary nerve repair is usually accomplished without difficulty with sufficient bone shortening. Three or 4 stitches of 8-0 or 9-0 Nylon suture provide adequate repair of digital nerves, but more sutures are required to repair major proximal nerves. Nerve grafts are used when direct repair cannot be accomplished. Donor nerve graft can be taken from nonreplantable digits, the medial antebrachial cutaneous nerve distal to the elbow, the posterior interosseous nerve above the wrist, or the saphenous nerve. While nerve repair is one of the simpler steps in replantation, the long-term function of the replant is largely dependent on nerve recovery.

Skin coverage is the final step in replantation. At this point, care must be taken to ensure that wound closure is without tension in order to avoid constriction of the delicate vascular repairs. Routinely, the midlateral incisions on the digits are not closed. Fasciotomies are indicated for proximal major limb replantations. Local rotation flaps are used to cover anastomoses with viable skin when required. Skin grafting is typically deferred to a second procedure 3-5 days after the initial replantation in cases of soft tissue loss.

Before applying the dressings, I routinely place an indwelling catheter percutaneously adjacent to the median nerve to provide continuous infusion of 0.5% bupivicaine, which creates a sympathetic block limiting vasospasm postoperatively[66] (Fig. 4.9). At the completion of the operation, the hand is dressed in layers with nonadherent petrolatum-impregnated gauze, followed by dry gauze and a plaster splint. Care is taken to avoid any constriction of the replantation by the dressing.

Major Limb Replantation

Complications of major limb replantation can be life threatening and should be appreciated by the surgeon and the patient. In some cases, major limb replantation allows for better function than a prosthesis. The best of these results occur at the level of the midforearm to distal forearm. For more proximal injuries, the goal is to provide a functioning wrist and hand for simple hook-grasp and prehension with

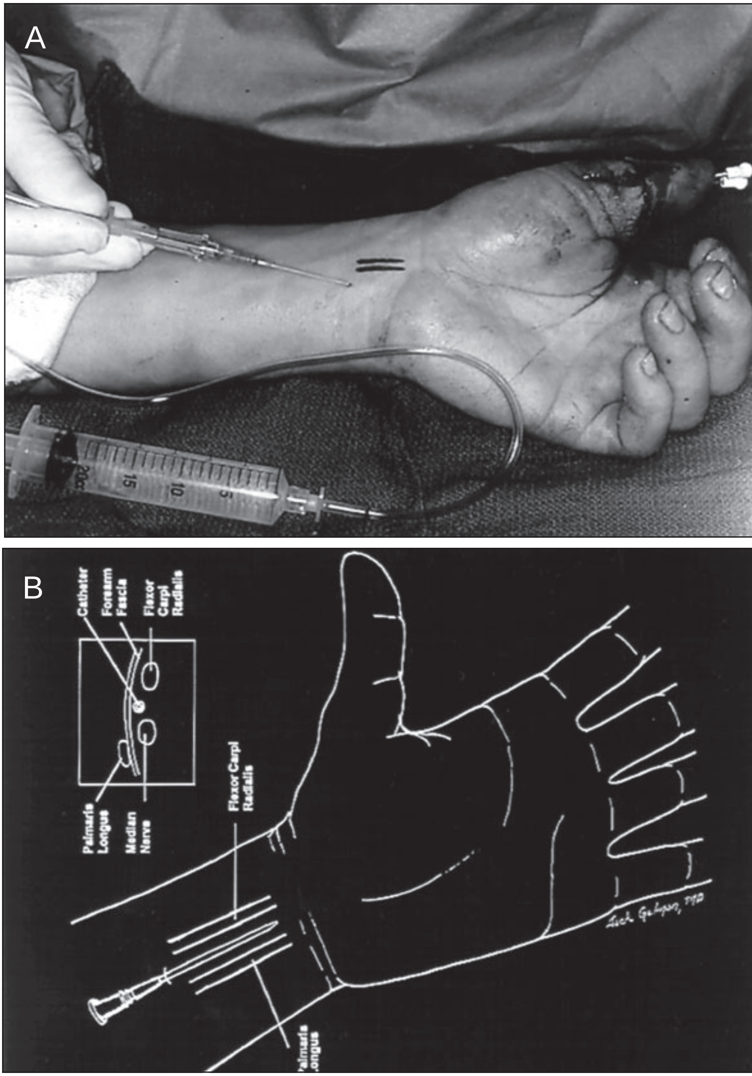

Fig. 4.9. A,B, A catheter is placed percutaneously adjacent to the median nerve to provide a continuous peripheral sympatholytic block with Marcaine (bupivacaine) to prevent vasospasm.

protective sensibility[60] (Fig. 4.10). Fasciotomy of the amputated part is routinely performed after debridement. Muscle tissue is sensitive to ischemia, thus, extensive debridement of both the detached part and the amputation stump is essential to prevent the absorption of toxic metabolites from necrotic muscle and infection.[61] In

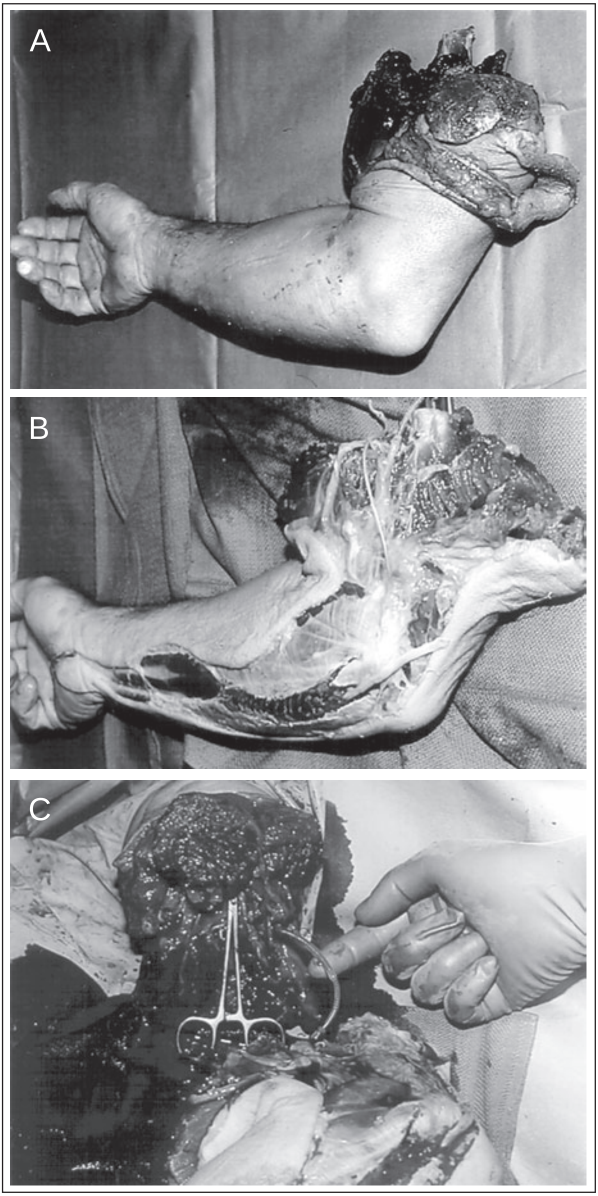

Fig. 4.10. A, Midhumeral complete amputation. B, Preparation of part by fasciotomy, bone shortening and plating, insertion of vascular shunt, all before induction of general anaesthesia. C, Initial hook-up of arterial supply via temporary shunt.

Fig. 4.10., cont., D, Appearance of replanted arm at completion of replantation.

major limb replantation, the surgical sequence is altered to restore the arterial supply quickly and limit myonecrosis. In replantation proximal to the metacarpal level, a vascular shunt is used initially to restore the arterial supply (Fig. 4.11). After that point, bone stability can be achieved while the limb perfuses. The limb is allowed to perfuse before reestablishing venous repair to purge accumulated toxic metabolites from necrotic muscle. Care must be taken to avoid excessive exsanguination because bleeding can be significant and life threatening. After re-establishing the circulation, tendon and nerves can be repaired. The patient is given a bolus of sodium bicarbonate before establishing venous return and is monitored closely for signs of systemic acidosis. After major limb replantation, the patient is returned to the operating room for evaluation of the muscle tissue and redebridement within 48-72 hours.

Postoperative Care

Postoperative management of the replantation patient is critical in achieving success. Postoperatively, the patient should be protected from vasospasm, pain, anxiety, tobacco smoke, cold temperatures, and caffeine, which can contribute to vasospasm during the first two weeks after surgery.[62-63] The patients room is kept above 21°C (70°F) The hand is placed on a soft pile of blankets or in a foam cradle at heart level. If arterial inflow is a concern, then the hand is lowered. If venous engorgement is present, the hand can be elevated.

I routinely use some form of systemic anticoagulation. Most commonly, I employ a combination of aspirin 325 mg per day and intravenous heparin, adjusting the heparin to increase the partial thromboplastin time to 1.5 times control for 5-7 days. Care must be taken not to anticoagulate patients to the point of bleeding complications. For more proximal major limb replantations heparinization is not routinely carried out and Dextran 40 (500 cc per day) is given instead.

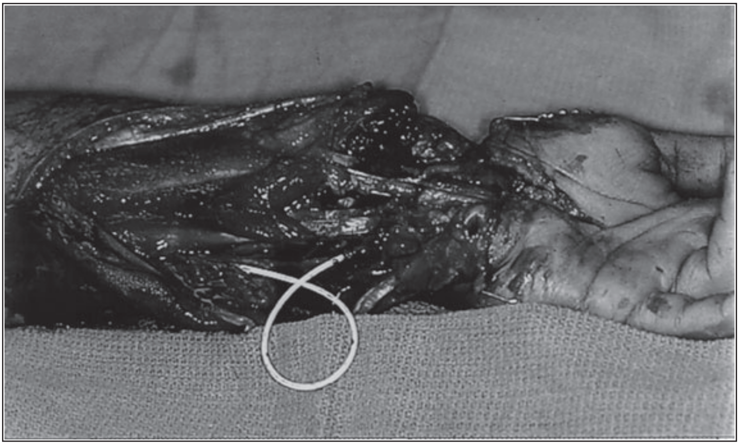

Fig. 4.11. Revascularization in major limb injury starts with placement of an arterial shunt to limit ischemia time and myonecrosis.

Oral pain medication is given to provide comfort and reduce anxiety. Chlorpromazine (Thorazine) 25 mg is given three times a day to relieve anxiety and provide peripheral vasodilation. Hydration with saline solution is maintained at 125 cc to 150 cc per hour for the first 5 days. The replanted part is monitored for color, turgor, capillary refill, and warmth. Surface temperature monitoring of the digit has proven useful in indicating adequate vascularity of the digit. A surface probe is attached to the skin of the replanted part, and periodic recordings of the part are taken by the nursing staff. If the temperature falls below 30°C, the part is assumed to have poor perfusion, and the cause for the compromised circulation is located and corrected. Other techniques of monitoring the digit include transcutaneous oxygen measurement and laser Doppler flowmetry.[64]

At the conclusion of the case, I routinely place a catheter adjacent to the median nerve at the level of the distal forearm and infuse bupivicaine 0.5% at a rate of 2 cc per hour to provide peripheral sympatholysis for 5 days postoperatively. This provides excellent pain relief in addition to its sympatholytic effect. If the catheter malfunctions, it can easily be replaced percutaneously at the bedside.

If the replanted part appears to be in jeopardy, several actions can be taken to reestablish flow. First, the patient should be evaluated for hydration status. If dehydrated, then a 500 cc saline bolus can be administered. A bolus of heparin can be given to reverse vascular clotting. Removal of factors that may be causing anxiety may prove useful. When a sudden loss of perfusion is evident, return to the operating room for re-exploration to remove a thrombus, reanastomosis, or vein graft can save a failing replant but must be done within 4 to 6 hours of perfusion loss to be successful. When venous congestion is unrelieved by position change, leeches can be applied (Fig. 4.12). Rarely is re-exploration beneficial after 72 hours postreplantation.

Fig. 4.12. Application of leeches was successful when venous cogestion developed in this replanged thumb 48 hours postoperative.

Results

Nerve recovery after replantation is comparable to that of a primary isolated nerve repair. Two-point discrimination in the digits averages 10 mm-15 mm,[65] and recovery of sensibility is better in children and patients with more distal replantations.[66] Range of motion varies depending on the level and the extent of injury. Cold intolerance is similar to that encountered in amputation stumps and typically improves after 24 months. The appearance of the replanted part usually is well accepted and preferred to prosthesis. Replantation continues to provide useful restoration of the traumatized extremity when cases are properly selected.

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Microsurgical Reconstruction of Type IIIB and IIIC Open Fractures in the Lower Extremity

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Introduction

When a severely injured or devascularized lower limb to be amputated and when should salvage be attempted ? Also, if the initial attempt in salvaging the limb is successful, what is the appropriate strategy for reconstruction? These are the most difficult questions faced by the orthopaedic traumatologists. With few exceptions, the decision is never clear-cut and it is extremely difficult in the immediate postinjury period to select who would be better off with an amputation.[1,2]

High energy injuries from motor vehicle crashes and industrial accidents may cause severe comminution of bone, a crushing insult on soft tissue and complete devascularization of either the distal part of the leg or of an extended segment of bone and soft tissues. In all high grade open fractures including blunt type IIIC injuries (requiring vascular repair) and some type IIIB injuries with very extensive crushing zone and involvement of all muscular compartments and nerve damage, primary amputation should be considered. Although the osseous damage is obvious on x-rays, the degree of soft tissue involvement may be assessed only indirectly.

Recent advances in trauma management and support, vascular reconstruction, nerve grafting and vascularized tissue transfer have dramatically extended the surgeon's ability to salvage a severely injured limb.[3,4] However, not all injured extremities can benefit from these modern reconstructive techniques and there is still an ongoing debate regarding the criteria that predict successful salvage of severely injured extremities. The number of cases selected for limb salvaging varies from 25 up to 40% in some more recent series. In contrary several orthopedic surgeons, considering amputation as failure of their therapeutic intervention, not infrequently have attempted to preserve a functionless limb in a costly, highly morbid and sometimes lethal reconstructive process.

Factors Affecting Limb Salvage and Outcome

The most critical factor that will predict the failure of a salvage attempt is vascular injury from blunt trauma, particularly at the infrapopliteal level. Warm ischemia time of more than 6 hours has been suggested as an absolute indication for amputation.

The degree of the soft tissue damage is the next most important predictive parameter even if adequate perfusion maintains the viability of the foot. The problem usually arises from the compromised blood supply to the crushed musculature resulting in widespread necrosis. This subsequently leads to difficulty in obtaining bone union, to a high incidence of infection and eventually to amputation. The absence of sensation in the sole of the foot as a result of irreparable extensive avulsion injuries of the sciatic or the tibial nerve is also an indication for primary amputation. Additional factors related to the preinjury health profile of the patient, other comorbidities, the age of the patient, the presence of shock or compartment syndrome, severe initial contamination and the delay between the injury and definitive care in a trauma center all have important prognostic implications. The desire of the patient should also play a role in the decision about the fate of an injured limb.

It is important to distinguish results of salvage between the upper and the lower extremities as different and the criteria for salvage also been different. A severely injured upper extremity has a much greater impact on the overall function of the patient than does a lower extremity. The results of nerve repair are better in the upper extremity than in the lower extremity, as the target organs are closer to the site of the repair. On the other hand a patient with a below the knee amputation wearing his prosthesis has much better function compared to a patient with a forearm+hand prosthesis for a below the elbow amputation.[4]

There are also significant differences between injuries above and below the knee. The functional outcome after a transfemoral amputation is poorer than that after a below the knee amputation. Moreover, reconstruction of vascular injuries is frequently easier above than below the knee, the outcome after nerve repair above the knee in adults is poor, and the thicker soft tissue envelope above the knee makes soft tissue reconstruction easier.

Scoring Systems End Effectiveness

In the recent decades a considerable body of literature is devoted to attempts to delineate the point at which the severity of the injury justifies immediate amputation.[33,35,36,67,69,70] Many investigators attempted to establish objectivity in the decision making process, which could eliminate the psychological and legal questions arising in the face of a mangled devascularized lower limb. To standardize the criteria for amputation different scores have been established such as the Hannover Fracture Scale (HFS), the Predictive Salvage Index (PSI), the Limb Salvage Index (LSI), the Mangled Extremity Syndrome Index (MESI) and the Mangled Extremity Severity Score (MESS). These are graduated grading systems based on skeletal and soft tissue injuries, shock, ischemia and age. Their clinical relevance has been evaluated in several studies. The MESS seems to have the highest specificity and it is most commonly used in clinical practice. In patients with MESS scores greater than seven, an amputation is commonly indicated. However, all these scoring systems have been criticised as being too complex, applied retrospectively to patients with known outcomes, being subjective and difficult to apply in a prospective fashion, derived from relatively small group of patients and not being validated by functional outcome data.[8-10] All scores are dynamic values which may vary with new developments and improvements of clinical treatments and no scoring system can absolutely predict functional outcome. Individual judgement about each patient is recommended.

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For those injured limbs that do not clearly meet the criteria for primary amputation, we believe it is reasonable to consider an initial salvage attempt, re-evaluation and if it is proven nonsalvageable after a frank discussion with the patient and his family, subsequent early secondary amputation.

When treating a patient with a severely injured limb, medico-legal issues involved in the decision for early amputation or salvage may arise and it is suggested to obtain and maintain in the medical record photographs of the limb at the initial and each stage of the treatment process. They provide invaluable documentation of the extent of injury to the limb as well as a visual record of the amount of progress toward a functional, salvaged extremity.

The current trends in orthopedics and the contemporary policies of the health care providers give strong consideration to the high cost of limb salvage in relation to the final functional outcome. When amputation is inevitable, performing surgery early enhances patient survival, reduces pain and disability and shortens hospitalization.[4] Few published studies have directly compared the functional outcome and the hospital cost of early amputation and limb salvage in the lower extremity.[2,5,6,9-13] Puno et al reported an average number of 3 operations in cases with primary amputation compared with 12-13 in cases with an attempt to limb salvage.[11,12] Moreover, in the patients with primary amputation none died compared with 21% mortality of the delayed amputation group.[13] In another study, patients with successful limb salvage had more complications, underwent more operative procedures, spent more days in the hospital and incurred higher adjusted hospital charges than did those who underwent early below the knee amputation. However, among the costs of amputations are not accounted the additional societal costs such as of retraining, a lifetime of disability reimbursements and workman's compensation.[13] Williams compared the costs of lower extremity amputation with the cost of Ilizarov reconstruction for limb salvage in a small group of patients.[13] He found the cost of amputation 45% less than the salvage cases. However, when the average projected lifetime prosthetic limb and supply costs were accounted, the amount escalated to 6 times higher than the salvage cases.[14]

When a quality of life evaluation questionnaire was applied, the limb salvage group considered themselves severely disabled, having problems with the performance of occupational and recreational activities.[13]

Limb Salvage

When a decision is made for salvage rather than amputation, the surgeon should have a frank discussion with the patient with full disclosure about what the salvage attempt may involve. This will allow him to assess the patient's motivation and desire before he starts a lengthy and demanding program aimed at limb preservation.

The advent of microsurgery introduced new alternatives in limb reconstruction particularly for the lower extremity.[3,4,7,16-18] Salvage of an open tibial fracture with a large defect of the soft tissues became feasible with free tissue transfer. Similarly, nerve injuries may be repaired with nerve grafts. The protocol for the management of a type IIIC open fracture is clearly defined: thorough cleaning with more than 10 L of normal saline, meticulous surgical debridement and early vascular repair. The ischemia time may be minimized with the use of a temporary vascular shunt tube followed by permanent vascular repair with a vein graft beyond the zone of injury. Skeletal stabilization with an external fixator is a safe way to stabilize the skeleton, Antimicrobial therapy includes IV antibiotics and local administration with antibiotic beads and formation of a closed protective pouch with adhesive dressings. Initial primary wound closure is usually not possible nor desirable.[3,4,7,16] The prevailing surgical approach toward emergency flap coverage of open fractures should not be applied in type IIIC fractures. After a second look in the wound and when myonecrosis in the zone of injury has subsided and the patient is stable, we proceed with soft tissue coverage either with a local flap or free tissue transfer. Unlike in the IIIB open fractures, some authors suggest that in type IIIC fractures the myonecrosis takes place for about 6 weeks and increases the risk of failure of any free flap due to reperfusion injury. In contrast, other investigators suggest soft tissue coverage earlier in the first 10 days from injury.[18]

Skeletal reconstruction follows, as soon as the wound is aseptic and stably covered. The host bone needs radical debridement down to bleeding cortical bone. Bone grafting may include early cancellous bone graft, vascularized bone transfer or the application of distraction osteogenesis techniques.

Microvascular reconstruction of the soft tissue envelope may be combined with the bone grafting based on the same vessels as a composite osteo-muscular tissue flap.[16-18]

The reconstruction of nerve defects in the very few cases where the limb is salvageable in spite of the severance of a nerve trunk should be carried out early as soon as soft tissue coverage is adequate.

Even if the most appropriate selection criteria have been applied for an attempt to salvage a limb, secondary amputation is always a possibility if severe complications occur.[17,18]

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Management of the Mangled Upper Extremity

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Introduction

The human hand is characterized by its unique capabilities of detailed sensation and movement. The forearm and brachium facilitate these vital functions by stabilizing and positioning the hand in space. Major trauma to the hand and forearm involves a variety of structures and disrupts their integrity and interactions. The viability of distally intact structures may be compromised by mangling injuries to the arm, forearm, and hand.

Although the evolution of repair and reconstruction techniques for each of the injured structures has helped to improve prognosis, the mangled upper extremity continues to challenge the treating surgeon and to have a severe impact upon the patient. Proper management is of utmost importance to reduce the disability resulting from these injuries.

The term "mangled" is commonly used to describe the hand and upper extremity after major trauma. Gregory et al used the term "mangled" to describe a severe injury to at least three of the four organ/tissue systems of skin, bone, vessel and nerve. According to the Oxford English Dictionary to mangle is "to reduce by cutting, tearing or crushing to a more or less unrecognizable condition" Each of these definitions imply a severe, high-energy injury, which involves multiple anatomical structures, usually over an extended topography.

Mangling injuries are produced by high-energy forces. High-power equipment, either agricultural (corn picker, grain auger), industrial (punch press, power saw) or household (lawn mower, snow blower) may cause such an injury. In addition, gunshot wounds, explosives and motor vehicle accidents (especially with the arm of the patient being outside of the car window) account for many cases. The injury may have a combination of sharp, crushing, avulsive, and thermal components. The wound may be severely contaminated, depending on the location and mechanism of injury.

Careful evaluation of both the patient and the injury, formulation of a treatment plan, meticulous operative treatment by an experienced team, and early, motivated rehabilitation reduce the morbidity associated with these injuries.

Patient Evaluation

Evaluation of the patient with a high-energy injury should include a thorough trauma evaluation, beginning with the basics of airway, breathing, and circulation

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(ABC's). While the mangled extremity is often the most apparent injury, careful evaluation of the entire patient for potential life threatening or other associated injuries is critical to formulating a treatment plan.

The patient history should focus on the time and mechanism of injury, and any associated chemical, electrical, or thermal components of the injury. The mechanism and the time from injury, when ischemia is present, are the most important factors in determining the zone of injury and predicting the ability to slvage the extremity. A medical history is taken to determine the patient's ability to tolerate a prolonged anesthesia with potential for significant blood loss, fluid shifts, and overload of metabolic by-products. Medical conditions such as diabetes, hypertension, vasculitis or other inflammatory diseases, and smoking history can adversely affect outcome and should be considered in developing a treatment plan. Similarly, the occupational and social history are important in determining postoperative compliance and in addressing the reconstructive goals. The presence of one or several adverse factors is not an absolute contraindication to salvage of an extremity or to microvascular repair. However, these factors should be considered in selecting the type of reconstruction to be used and in better predicting outcome.

Examination of the mangled extremity should be systematic and address the following: vascular status; skeletal stability; motor and sensory function; and soft-tissue loss. The vascular status is evaluated by assessment of peripheral pulses, color, temperature, and capillary refill time. Pulse oximetry is generally readily available in the emergency room and is very helpful in assessing ischemia. Doppler examination and angiography can also be used. Skeletal injury is assessed clinically by the presence of deformity, crepitance or bone tenderness. Tangential radiographs should be taken of the entire extremity. A motor and sensory examination should be documented. Motor and /or sensory loss can result from muscle, tendon, or nerve injury, as well as from ischemia. The ultimate assessment of the mangled extremity occurs in the operating room, after the debridement of nonviable tissue.

Adjuvant studies of the extremity include detailed radiographs and angiography. In the case of limb threatening ischemia, some studies may best be obtained in the operating room. An intraoperative angiogram may aid in determining the level and extent of arterial injuries. Color Doppler may be alternatively used. It is accurate, less invasive, and may also be used intra-operatively. Radiographs taken in the operating room are usually better quality than those taken in the emergency room, as the extremity can be positioned without causing the patient discomfort. Traction radiographs allow better delineation of the fracture pattern and number of fragments, especially in evaluating intra-articular fractures about the elbow. Photographic documentation of the injury should be done in the operating room.

Decision-Making and Planning

Salvage vs. Amputation

The surgeon may be confronted with the decision to attempt salvage or amputate a mangled, nonviable extremity. The appropriate decision is difficult, since recovery of function in a salvaged extremity may be limited or absent. Thus, multiple reconstructive procedures with associated morbidity, prolonged hospitalization, disability time, psychological distress and financial demands may be too expensive a price to pay for the end result of a useless and painful limb. In contrast to prostheses for the leg, prostheses for the hand and forearm offer very limited restoration of function. Thus, most mangled upper extremities should be considered for salvage. Nevertheless, serious associated injuries or diseases, ischemia time greater than 6 hours and parts that are severely crushed, avulsed, contaminated or injured at multiple levels, constitute unfavorable conditions for a replantation or revascularization attempt. In this setting, amputation is not a failure but rather a step towards stabilization of the patient and rehabilitation of the extremity.

In deciding how to best treat the mangled extremity, a variety of factors should be considered. They can be broadly classified as patient and extremity factors. Pertinent patient factors include the general condition, age, handedness, occupation, functional requirements and socio-economic background of the patient. Associated injuries resulting in cardiopulmonary or hemodynamic compromise, as well as preexisting medical problems will be against a lengthy salvage procedure, especially in a patient of advanced age. Conditions adversely affecting the blood vessels, such as diabetes mellitus, vasculitis and smoking will increase the risk of anastomosis failure and should be taken into consideration. Psychiatric disorders may be a contraindication to reconstruction, due to possible repeat suicide attempts or anticipated noncompliance with the rehabilitation program. A morose patient may be temporarily incompetent to participate in determining treatment. Since time is a critical factor in treatment, it may be better to err in attempting to salvage an extremity than to perform a primary amputation.

Important extremity factors comprise the time since the injury, the severity of the injury and the previous functional status of the extremity. Warm ischemia time greater than 6 hours results to irreversible changes in cellular structure of muscle. Even if vascularity is reestablished, tissue necrosis will not be avoided. Systemic risks of revascularizing a limb with prolonged ischemia must also be considered and addressed. These include acidosis, hyperkalemia, and rhabdomyolysis. In amputations of digits the delay until reperfusion may be extended to 20 hours. Finally, the previous condition of the extremity should be considered. A history of major trauma, neurological disease or congenital deformity resulting in impaired function may not justify a salvage attempt.

The multitude of factors and the complex interrelations among them make reaching a decision a difficult task, even for experienced surgeons. Specialized scoring systems have been developed based on lower extremity injuries. These may offer valuable guidelines for evaluating the lower extremity, but cannot be applied well to the upper extremity. Each case is unique. The final decision should be an individualized one, based on assessment of the patient and extremity parameters, as well as sound judgment. The patient's knowledge of the potential risks and benefits of surgery and the possibility of early or later amputation is important.

Timing of Reconstruction

Reconstruction of the mangled extremity may be undertaken either early or late. In both reconstructive plans, the initial treatment includes aggressive debridement, skeletal stabilization, revascularization, and soft tissue coverage. Early soft tissue coverage is of paramount importance to limb salvage. This improves the vascularity to the traumatized area, limits exposure to hospital pathogens and reduces the risk of infection. Coverage is technically easier to perform early, since with delay edema obscures tissue planes, vessels become friable and grafts may be needed to escape the zone of injury.

Reconstruction of bone, tendons and nerves is then performed either early or late. Early reconstruction is when all injured structures are repaired or reconstructed during the initial phase of treatment, up to ten days from the initial injury. Delayed reconstruction is when bone, tendon and nerve are reconstructed at later stages of treatment. The choice of the reconstructive approach is dependent upon the characteristics of the injury and the preference and expertise of the treating surgeon.

Delayed Reconstruction

Delayed, staged reconstruction in the past was the primary method of treatment of severe injuries with multiple structural defects. In this treatment plan, vascularity is established, and the soft tissue injuries are treated with serial debridements, performed at 24-72 hour intervals. Appropriate wound coverage is performed when the wound is clean and all necrotic tissue has been debrided. This should be within the first ten days from injury. Bone, tendon and nerve reconstruction are delayed until "soft-tissue equilibrium" is achieved. This is when the tissues have healed and are free of infection, edema has resolved, scar tissue has matured, and the joints are supple and have achieved their maximum passive range of motion.

Delayed reconstruction is a good option when patient co-morbidity or a severely contaminated or infected wound prevent early definitive treatment.

Early Reconstruction

This approach requires debridement of the wound, followed by reconstruction of all structures: bone, tendon, and nerve. This is done ideally within 24-72 hours. Primary corticocancellous bone graft or vascularized bone grafts, nerve grafts, tendon transfers, tendon grafting, or free functional muscle transfer are performed at the time of soft tissue coverage. Reconstruction can be delayed up to ten days, in the event of a severely contaminated wound, which requires several debridements to reduce the contaminant load.

Primary reconstruction of all structures is technically easier to perform acutely than later through a scarred tissue bed. It decreases the number of subsequent procedures, total hospitalization time and cost. Also, rehabilitation begins earlier. The development of adhesions is decreased, and the functional outcome is improved.

Principles of Treatment

General

Management of the mangled upper extremity is complex, demands special skills and expertise, and is facilitated by a team approach with participation of trauma, orthopedic and microvascular surgeons. When adequate facilities, equipment, or surgical expertise are not available to manage the patient's degree of injury, the patient should be transferred with the extremity splinted. If the limb is ischemic, or if part of the limb is amputated, the extremity should be cooled. The ischemic limb should be carefully covered in ice, with a protective barrier to prevent frostbite injury. The amputated part should be wrapped in a saline-soaked gauze, placed on ice and sent with the patient. The ideal temperature is (+) 4°C. Do not use dry ice or alcohol to transport the part.

Patient resuscitation is a priority over addressing the extremity injury. However, in the event of a coexisting life-threatening injury, the extremity injury must not be neglected. Assessment of vascularity, realignment and splinting are not time-consuming and should be done as soon as possible. Provisional revascularization through shunting may be an option to quickly restore circulation to the extremity, while the trauma team simultaneously addresses the co-existing injuries.

The patient should initially be consented for wide debridement of the wound, internal versus external fixation, repair or reconstruction as indicated of nerves, vessels, tendons, and muscles, use of vein grafts for arterial and venous reconstruction, and for primary amputation. The selected treatment will be based on intra-operative findings.

The initial treatment includes meticulous debridement, wound irrigation, obtaining wound cultures, antibiotic administration and tetanus prophylaxis. Copious irrigation of the wound is very important as it removes foreign bodies and decreases the bacterial load. The most predictive cultures of later infecting organisms are the postirrigation cultures. Antibiotics will help reduce infection and should be administered in the emergency room and continued intravenously for at least 72 hours. Antibiotic coverage should be effective against both Gram positive and Gram negative organisms. We currently use a 1st generation cephalosporin and an aminoglycoside, In cases of soil contamination, as in farm injuries, coverage against anaerobic organisms should always be added. High dose penicillin provides excellent anaerobic coverage. The possibility of gas gangrene should also be considered in these cases. The antibiotic regimen can be subsequently modified according to the culture results. Tetanus prophylaxis should be administered in accordance with the status of previous immunization.

Debridement

Radical debridement with elimination of all nonviable tissue is a crucial step in the management of these injuries and is performed under tourniquet control to provide the best visualization of the extent of injury and to prevent iatrogenic injury to intact structures. Once nerves and vessels are identified, the tourniquet may be released, to better assess the viability of the remaining tissue.

Skin and subcutaneous tissue are sharply debrided back to bleeding edges. Muscle is debrided until bright red blood is seen. Color and twitch are used to assess muscle tissue; however, these characteristics are less reliable in determining viability. If the muscle does not bleed, it is dead and should be debrided. Bone fragments devoid of soft-tissue attachments are avascular and should be discarded unless they constitute part of an articular surface. Contused or contaminated nerves are left in continuity. Superficial dissection above the epineurium can be carefully done to remove foreign material if present. Cut nerves are debrided back to healthy appearing fascicles. At the time of reconstruction, this should be done under microscopic visualization, as a primary repair or nerve graft will fail if the injured segment is not resected.

The wound is copiously irrigated. Tissue margins are reevaluated and further debridement is performed as necessary. Hemostasis should be done cautiously. Do not cauterize vessels that may be needed for arterial or venous reconstruction. Arterial debridement is performed for cut or thrombosed vessels. Definitive debridement of arteries, which are to be reconstructed, is done with the tourniquet released.

At the completion of debridement, assess and record what structures remain intact and what the functional losses are. Some of the remaining intact muscles may be suitable for immediate tendon transfer to replace important functional losses.

Provisional Revascularization

When the extremity is amputated or ischemic, and the delay to surgery or anticipated length of time for debridement and definitive skeletal stabilization exceeds 6 hours, then provisional revascularization can be done using a shunt, such as a Fogarty catheter or plastic tubing. Another option is to perform reversed vein grafting to re-establish arterial inflow. After definitive skeletal stabilization, the length of the vein graft can be adjusted.

Skeletal Stabilization

Definitive stable internal fixation should be done immediately to allow access to the extremity and early joint range of motion. In general, we try to avoid the use of external fixation. These devices carry the risk of neurovascular injury during pin placement, restrict circumferential access to the extremity and limit rehabilitation. They may be useful as a temporary solution for severely contaminated wounds with extensive soft-tissue injury. External fixation should not be used to avoid having exposed hardware. Exposed hardware should be addressed with appropriate soft-tissue coverage.

Diaphyseal fractures of the arm and forearm are usually amenable to plate fixation. If the fracture is segmental, or is comminuted over a large segment, a flexible inter-locking medullary nail can be used. Fractures should be reduced anatomically with respect to rotational alignment. Comminuted fragments without soft-tissue attachments should be removed. Shortening of the humerus up to five centimeters and of the radius and ulna up to four centimeters can be acceptable. Indications for shortening include significant comminution over a segment, or bone and soft-tissue loss. Shortening may allow primary repair of vessels and, more importantly of nerves.

Complex diaphyseal fractures include Galleazi fractures (radial diaphyseal fracture with disruption of the distal radio-ulnar joint), Monteggia fractures (proximal ulna fractures with radial head dislocation or radial head or neck fracture), and Essex-Lopresti injuries (radial head fracture with associated rupture of the interosseous membrane to the level of the wrist). These fractures must be restored to anatomic length in order to restore joint congruity and alignment.

Diaphyseal fractures of the hand should be fixed with Kirschner wires, with attention to maintaining rotational alignment. Shortening of the metacarpals or phalanges between 5 and 6 mm may be necessary in replantation. For other injuries, length can be restored or maintained with internal or external fixation and primary or delayed bone grafting. In general, we do not recommend use of plate fixation in the hand, particularly in the phalanges. This requires more stripping of the periosteum and later has an adverse affect on functional outcome due to adhesions around the plate.

In contrast to lower extremity injuries, primary bone grafting is acceptable and recommended in the upper extremity. Primary iliac crest bone graft or bone allograft may be used for defects up to 4 cm. For larger defects, vascularized bone grafts, in particular the vascularized free fibula should be considered. With massive bone loss, creation of a one-bone forearm can be considered as a salvage procedure when other options are not available. The results of this procedure in trauma are not as good as in limb saLVAglvaee surfor tumor reconstruction.

Intra-articular fractures should be anatomically reduced. Stable fixation is imperative to allow early range of motion. Fixation can be done with plates, screws, K-wires, and tension band wiring as dictated by the fracture pattern and location. Articular fragments free of soft-tissue attachments should be preserved to reconstruct the joint surface. Primary bone grafting should be done to address bone defects, to enhance the stability of the fixation and to promote bone healing. When the joint surface cannot be reconstructed due to severe comminution or bone loss, other reconstructive options are available. At the shoulder and elbow, primary allograft or prosthesis can be used. At the wrist joint, primary fusion should be the first treatment option. If wrist motion is critical to the patient, then vascularized free fibula, retaining the proximal articular cartilage can be used to reconstruct the joint surface. Total wrist arthroplasty historically does not do well in posttraumatic wrists.

In summary, the goals of skeletal stabilization are to achieve stable anatomic fixation to allow early range of motion and rehabilitation. Soft-tissue stripping of bone should be limited to only that which is necessary for fixation. Comminuted fragments with attached soft-tissue should be retained. Bone defects should be treated primarily whenever possible. The potential of exposed hardware should not limit the choice of fixation. Exposed bone, hardware, or joints should be addressed with appropriate soft-tissue coverage.

Vascular Reconstruction

Definitive revascularization should be done once skeletal stabilization is completed. Lacerated vessels should be resected to healthy appearing vessel wall both proximally and distally. Contusion along the adventitia suggests injury within the intimal layer as well. A "ribbon sign" (convoluted or tortuous course of the digital vessels) indicates injury to the media layer of the vessel and requires resection of the length of the involved area and reverse vein grafting. Inflow should be assessed and if not adequate, the vessel should be resected more proximally until excellent pulsatile flow is achieved.

When possible, primary repair is preferred. However, it is better to resect appropriately and use a reversed vein graft than to perform a primary repair under tension. Reversed vein grafts are available from several sites. The most commonly used for long segments in the upper extremity is the saphenous vein. For reconstruction in the hand, local grafts from the dorsal or volar forearm can be used. Reconstruction of the superficial palmar arch can be difficult. Branched vein grafts from the dorsum of the foot or use of the scapular artery and its branches have been described. Our preferred method is to harvest two "Y" vein segments from the volar forearm and perform end-to end or end-to-side anastomoses as necessary. Vein grafts should be routinely used to reconstruct venous outflow if primary repair cannot be achieved. There is almost no role for artificial grafts for vascular reconstruction in the upper extremity distal to the axillary artery.

Musculotendinous Reconstruction

Primary tendon repair is preferred when permitted by the injury. Often, there is a crush or avulsive component to the injury, which precludes primary repair. In these cases, treatment options include primary or delayed reconstruction with tendon grafts or silastic rods. We favor immediate reconstruction using available donor tendons (palmaris, plantaris, local tendons which cannot be reconstructed and toe extensors).

In flexor tendon injuries in the hand, priority is usually given to reconstruction of the profundus tendon. If there is trauma to the DIP joint requiring fusion, then priority is given to the superficialis tendon. The lesser priority tendon can be used for reconstruction of the other when necessary. It can be used as a donor tendon for other sites or for pulley reconstruction as necessary. Irreparable injuries to the A2 and A4 pulleys should be addressed using available donor tissue.

Functional reconstruction of muscle deficits and tendon injuries should be done immediately. Unrecoverable muscle function can be treated with tendon transfer. We favor primary tendon transfer. However, this can also be performed at a later stage of reconstruction. Delayed transfers are generally more difficult, as they have to be performed through a scarred tissue bed, and this requires additional surgical procedures and further delays patient rehabilitation and recovery. When no donor tendons are available for transfer, muscle function can be restored with functional free muscle transfer. The gracilis is the most commonly utilized muscle for functional reconstruction. Again, this can be done either primarily or at a later stage of reconstruction. We again favor primary reconstruction.

Nerves

Nerves may have internal derangement without loss of continuity. They may be partially or completely disrupted. Contused or attenuated nerves are spared. If lacerated, the nerve ends should be debrided under the microscope to healthy appearing fascicles. Do not compromise the resection in order to preserve length. Nerve regeneration will not occur through scarred nerve tissue and nerves repaired under tension also do not recover well.

Mobilizing the proximal and distal stumps to achieve primary repair is not recommended as this results in desvascularizing large segments of the nerve. Mobilization can be done over a 1-2 cm distance to allow repair. To avoid repair under tension, nerve grafting is performed. If a staged repair is planned, nerve ends are tagged with 6-0 prolene suture for later identification. We recommend primary nerve grafting. Common donor nerves include the sural or saphenous nerves, sensory branch of the radial nerve (if lacerated from the injury), medial or lateral antebrachial cutaneous nerves, and the posterior interosseous nerve. In multiple nerve injuries, primary nerve transfers can be performed. These include transfer of the anterior interosseous nerve (distal to the branch to the flexor pollicis longus) to the motor branch of the ulnar nerve or transfer of the sensory branch of the radial nerve to the digital nerves of the thumb and index finger. When a nerve defect is greater than 15 cm, an end to side anastomosis of the distal stump of the injured nerve to a neighboring intact major nerve can be done.

Skin and Soft Tissue Reconstruction

Appropriate soft tissue coverage is of paramount importance for coverage of bone, joint, tendons, neurovascular structures, and hardware. The selection of coverage should provide a gliding surface for mobile structures and enhance vascularity in the injured area.

Extensive skin and soft tissue loss is one of the major problems in the mangled upper extremity. Isolated skin loss may be managed by split thickness skin grafting (if not over a bony prominence, hardware or exposed tendons). Local random skin flaps have limited utility even in superficial soft tissue defects, due to their restricted mobility, precarious blood supply and frequent involvement in the injury.

Skin loss over a bony prominence, hardware or exposed tendons, as well as defects of the soft tissue envelope can be managed in a variety of ways. A simple approach is to leave the wound open and let it heal by secondary intention with granulation tissue. However, exposed tissues sensitive to desiccation, such as nerves and tendons, will become necrotic, scarring will be promoted and function will be compromised. Local muscle flaps are usually not suitable due to their participation in the injury, the limited amount of coverage that they provide and the resulting functional deficit. Two-stage distant pedicle flap procedures are avoided when possible, since immobilization of the reconstructed area will lead to stiffness.

In mangling injuries, the need for extensive coverage, reliable vascularity of the flap and early mobilization usually necessitates use of axial flaps (local or regional), one-stage distant pedicle flaps, or free flaps. The type of coverage depends on site and extent of the defect. This is particularly important for bone, tendon, nerve and hardware coverage, as well as for facilitation of future reconstructive procedures, when planning a staged reconstruction.

Fasciocutaneous flaps are recommended when tendons are exposed. They facilitate tendon gliding. However, most fasciocutaneous flaps over time do not have a good cosmetic appearance. The only fasciocutaneous flap we have used with acceptable cosmetic appearance has been the radial forearm flap, either as a free or rotational flap. An alternative to the fasciocutaneous flap is a fascial flap. Donors for this include the temporoparietal fascia, the parascapular fascia, and the radial forearm fascia. The free fascial flap is then covered with an unmeshed split-thickness skin graft.

Muscle flaps are used when a moderate to large soft tissue defect is present. Although muscle flaps may be harvested with a skin component, we prefer to harvest muscle alone. This is then covered with a nonmeshed split-thickness skin graft. In the arm and elbow, the latissimus dorsi can be used as a one-stage distal pedicle rotational flap. Most other reconstructions are done with a free muscle transfer using the gracilis, rectus abdominis, latissimus dorsi, or serratus anterior. When a functional deficit is present, consideration should be given to using a functional free muscle transfer to provide both functional restoration and soft-tissue coverage. The gracilis is most commonly used for this transfer.

Postoperative Management

In the immediate postoperative period the extremity should be splinted in an appropriate position to prevent capsuloligamentous shortening and tension on repaired structures. Elevation is necessary to reduce edema and help control pain. The patient's pain and anxiety should be adequately controlled. The ambient temperature should be at least 25˚C and adjusted to the patient's body temperature. Hydration should be sufficient to maintain a urinary output between 80-100 cc/hr. Anticoagulant therapy is used by many surgeons. However, we are very selective in using either heparin or Dextran. We do use daily aspirin for four to six weeks following surgery. Appropriate antibiotic therapy should be continued and later modified according to the culture results.

Flap monitoring is critical. Early recognition of arterial hypoperfusion or venous congestion will only occur in a well-monitored environment, with trained nursing staff. If there is a question regarding tissue viability, the dressings should be released and the whole revascularized tissue should be exposed for further assessment: perfusion, congestion, temperature, turgor, color and Doppler exam. Release of the dressings alone may be sufficient. If viability is still in question after 30 minutes, immediate re-exploration and further assessment may prevent failure of the revascularized tissue.

Early and motivated rehabilitation of the extremity is an important factor in achieving a successful outcome. Early motion reduces edema, adhesions, and scarring. It prevents muscle atrophy and it facilitates healing of the soft tissues by remodeling of collagen fibers. The details of the rehabilitation program are determined by the existing injuries and the reconstruction procedure.

Conclusions

Management of the mangled upper extremity is demanding and requires technical expertise, good judgment, considerable experience and specialized resources. Therefore, it should not be undertaken by every surgeon at every institution. The patient should be referred to a center where appropriate resources and expertise are available.

Case Presentations

Case 1

This 29-year old farmer sustained a crush-avulsion amputation injury of the left forearm from a combine machine (Figs. 6.1).

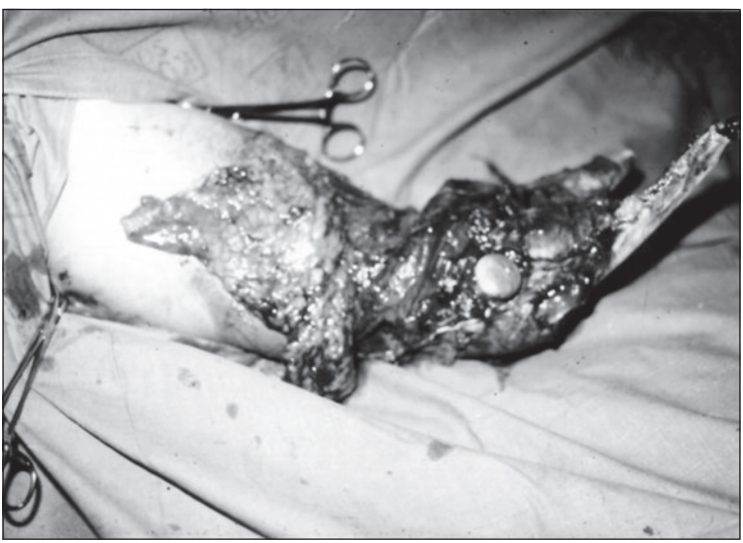

Fig. 6.1A. Proximal stump of the forearm with radial head dislocation and avulsion of the soft tissues to the level of the distal arm.

Fig. 6.1B. Amputated forearm.

Fig. 6.1C. Radiographs of the proximal stump, demonstrating a dislocated floating proximal radial stump.

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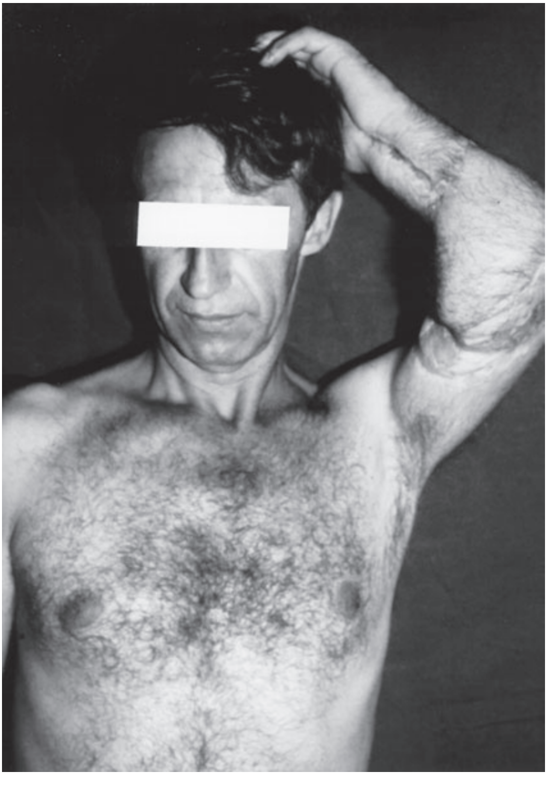


Fig. 6.1 D, E. D, One week following replantation of the forearm. A lattisimus dorsi free flap was used immediately for soft tissue coverage. An end-to-end reversed saphenous vein graft was used to reconstruct the brachial artery. The thoracodorsal artery of the latissimus dorsi muscle was supplied through an end-to-side anastomosis to the reversed saphenous vein graft. E, Appearance of the extremity nine months following replantation.

Case 2

A 25-year old factory worker sustained a sub-total amputation of the right forearm when his forearm was caught by a rotating chain (Fig. 6.2).

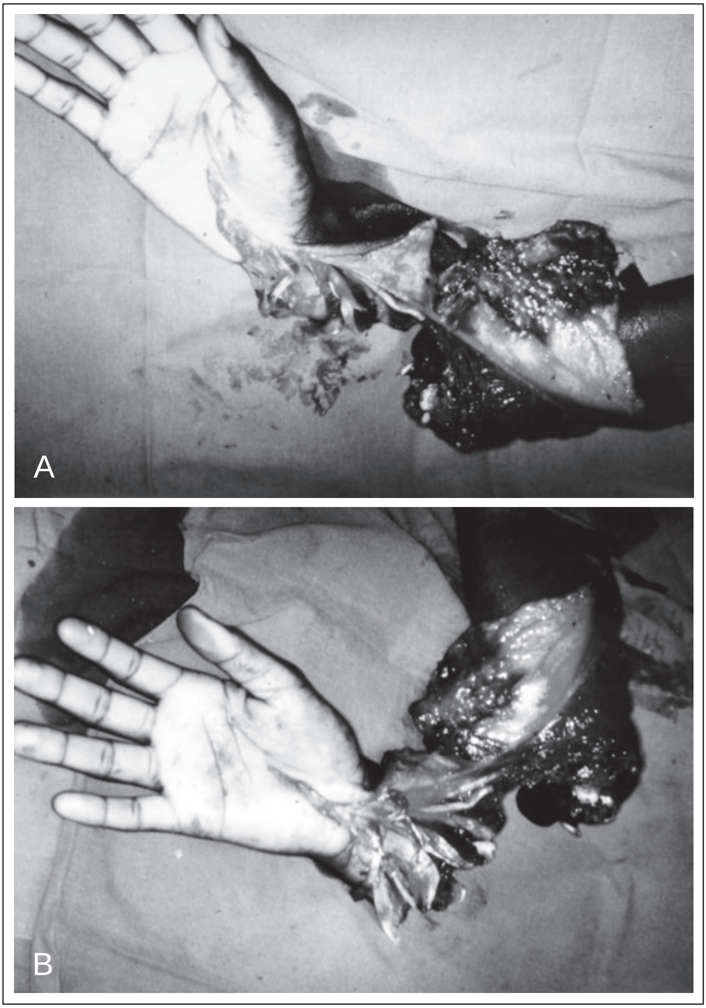
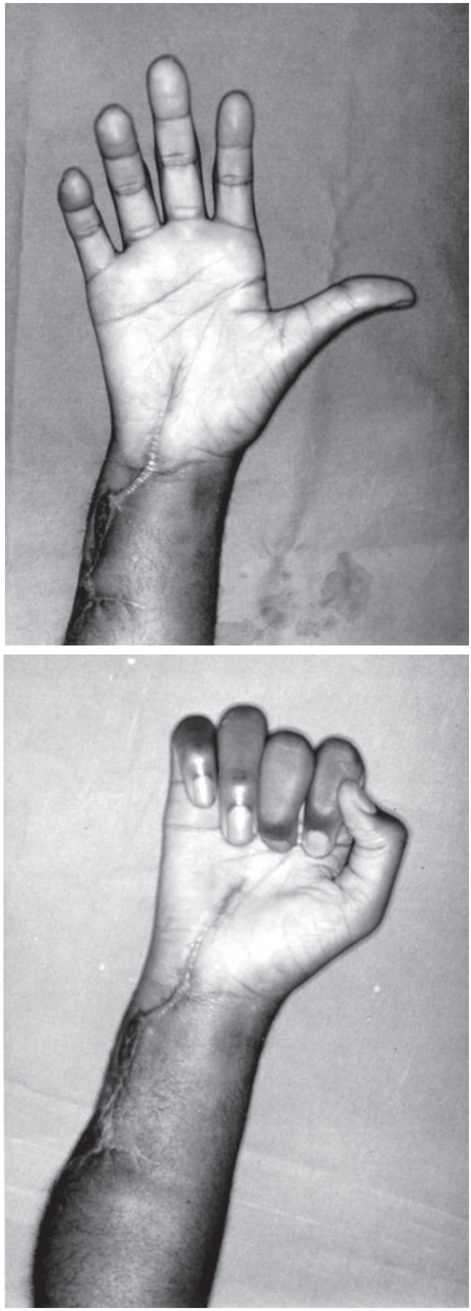


Fig. 6.2A and 2B. The sub-total amputation at the middle third – distal third junction of the forearm is demonstrated. The patient was treated with immediate shortening and fixation of both the radius and ulna, revascularization by primary repair of the arteries, reconstruction of venous outflow and repair of all lacerated structures, including median and ulnar nerves, extensor and flexor compartments.

Fig. 6.2C and 2D. Functional outcome six months following the surgery.



Case 3

A 35-year old man was involved in a motor vehicle accident. The dorsal aspect of his right hand and forearm were denuded of all soft tissue covering. The dorsal third of the carpus and distal radius were abraded. Only the thumb, index metacarpal and middle and third phalanx of the long finger were spared (Fig.6.3).

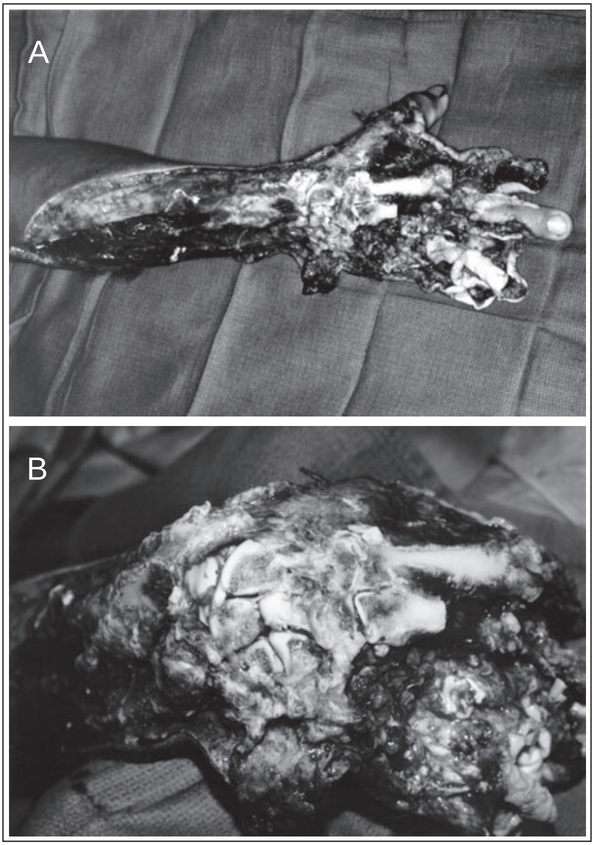
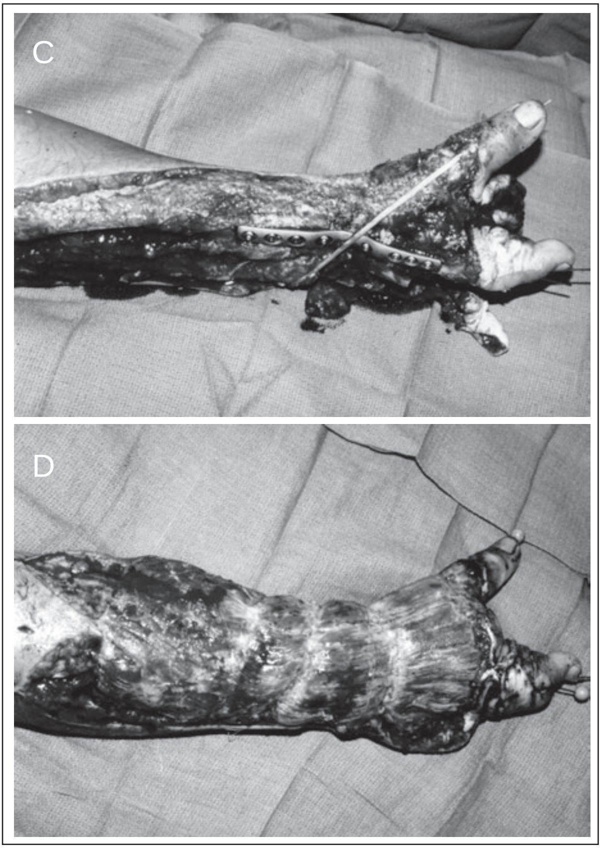


Fig. 6.3A and 6.3B. Dorsal forearm and dorsal hand at presentation.



Figs. 6.3C and D. C, Appearance of the hand following debridement, wrist fusion (along the index metacarpal) and transposition of the middle and distal phalanx of the long finger to the index metacarpal. Reconstruction of the extensor pollicis longus with palmaris longus tendon graft to the flexor carpi ulnaris was done immediately. D, Primary soft tissue coverage of the soft tissue defect was done with a free rectus abdominis muscle flap.

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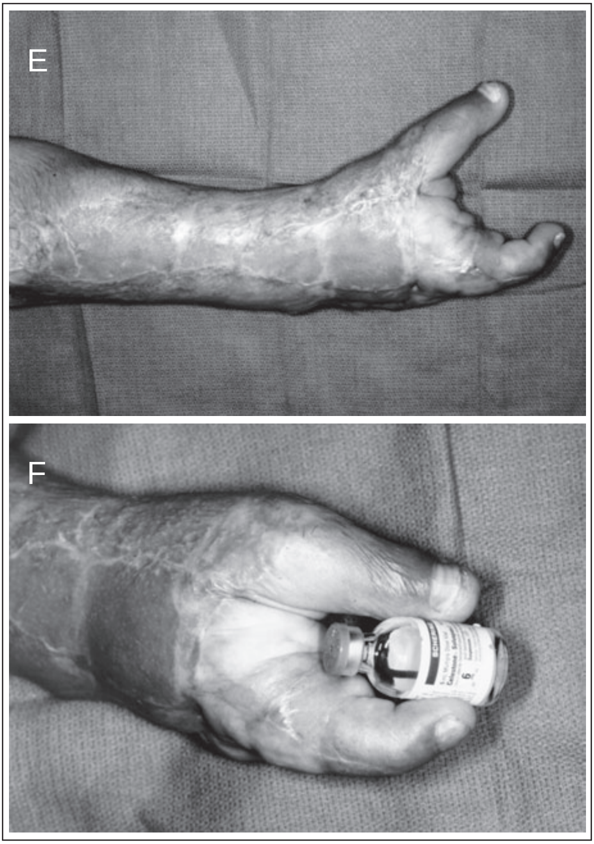

Figs. 6.3E and F. Functional and cosmetic appearance seven months following reconstruction.

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Single Stage Free Tissue Transfer

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Single Stage Free Tissue Transfer

Transfer of free vascularized tissue has become a widespread technique and the most reliable means of reconstructing major defects.

In actuality tissue transfer started in an experimental clinical setting in the middle of the 20th century with kidney transplantation, which gradually became the common place procedure it is today.[47] Later, in 1962, Nakayama of Japan transferred segments of jejunum for esophageal reconstruction using a vascular "ring-pin" stapling device.

Nakayama focused on his device but only casually mentioned the first vascularized autologous tissue transfer in human.[63] Following laboratory demonstrations of the feasibility of microsurgical free tissue transfer[24,45,79,81] in1972 McLean and Buncke successfully reconstructed the scalp with a free omental transfer[58] and finally in 1973 Daniel and Taylor in Australia reported a successful free flap, transferred from the groin to the lower extremity.[13]

Progress has been rapid since then. Efforts were directed not only to the reconstructive challenge, but also to identifying suitable donor flaps. Increased understanding of vascular anatomy and the introduction of the myocutaneous flap brought new dimensions to composite tissue transfer. Varied tissues—skin, bone muscle, fascia, peripheral nerve, omentum and intestine—indeed any part of the body supplied by blood vessels with a diameter greater than 0.5 mm., have all been transferred successfully.

The possibilities of clinical reconstructive microsurgery are almost unlimited and develop according to the innovative ability and the technical proficiency of the reconstructive microsurgeon. In the future, if the problems of rejection and immunosuppression are overcome or if cloning produces new organs, the unlimited horizon for "spare parts" surgery, which already has started, may develop even further.

Indications, Advantages, Contraindications, Disadvantages

The primary indication for free flap transfer is the presence of a tissue defect due to trauma or disease that cannot be closed by simpler methods. Less apparent indications include the need to improve local circulation by using a well vascularized muscle flap, as in the treatment of osteomyelitis, or radiation necrosis, the need for vascularized bone in reconstituting a long segmental bony defect, the need to give motion to the face following facial paralysis or to a paralyzed functionless limb and the need to restore sensibility to an anesthetic area of the hand or the weight bearing surface of the foot. Demands vary according to location and circumstances.

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Salvage or Amputation?

For extremity reconstruction and particularly for the lower extremity, there is another consideration in the decision whether to use a free flap; that is under what circumstances is salvage of the extremity indicated.[35,46] If valid indications for amputation are present, the patient will not be served well by a free tissue transfer. This only postpones the inevitable and prolongs hospitalization and suffering, but also results in poorer outcome compared with patients treated with primary amputation.[74]

The absolute indications for amputation include:

1. irreversible devascularization of the extremity
2. massive tissue loss, that is beyond our present capabilities for an adequate reconstruction of a functional limb and
3. septic gangrene.

Other factors however such as:

1. the general condition of the patient and the associated injuries
2. the vascular status of the limb prior to the injury and our capability to restore adequate circulation
3. the sensory nerve function
4. the degree of contamination
5. the extent of soft tissue and bony loss and
6. the desire of the patient may play a role in the decision about the fate of an injured limb.

7

In every case, the surgeon should have a frank discussion with the patient with full disclosure about what a salvage attempt may involve, in order to assess its motivation and desire before embarking on a lengthy or complicated program aimed at limb conservation.

A considerable body of literature is devoted to attempts to delineate beyond any doubt, the point at which the severity of the injury justifies immediate amputation.[33,35,36,67,69,70]

To standardize the criteria for amputation different scores have been established such as the Hannover Fracture Scale (HFS),[74] the Predictive Salvage Index (PSI),[7] the Limb Salvage Index (LSI),[64] the Mangled Extremity Syndrome Index (MESI)[15] and the Mangled Extremity Severity Score (MESS).[61,77] These are graduated grading systems based on skeletal and soft tissue injuries, shock, ischemia and age. Their clinical relevance has been evaluated in several studies. The MESS seems to have the highest specificity and it is most commonly used in clinical practice. In patients with MESS scores greater than seven amputation is, commonly indicated. Any index however, although useful in predicting limb salvage is not sufficiently accurate to be considered absolutely reliable. Individual judgement about each patient is recommended. All scores are dynamic values which may vary with new developments and improvements of clinical treatments and no scoring system can absolutely predict functional outcome.

Wound Location and Kinetics

In considering the tissue defect, thought must be given to the anatomic location and the etiology and nature of the wound and to the wounding agents and their kinetics. In high velocity wounds the zone of injury may be more extensive than the apparent size of the external defect. This effects the quality of local tissues that may be viable, but the degree of their contusion and circulatory impairment may be so extensive that any attempt to provide coverage by shifting them will cause necrosis. In such patients free flap coverage is the only satisfactory alternative.

Indications and requirements for reconstruction vary according to the level of the extremity injury. The more proximal the wound, the greater the likelihood that local tissues, can be used for closure and therefore fewer the indications for free flap transfer. Salvage of the elbow or the knee joint in conjunction with a below elbow or a below knee amputation represents a special situation; here local muscles are not always available. The benefits of maintaining a functioning knee or elbow joint and of avoiding a higher amputation are so great that closure with a vascularized tissue transfer (Fig. 7.1), may be worth the attempt.[19,76]

Below the elbow or knee free flap coverage is indicated for large defects in which there is exposed bone or in the distal third of the leg where, because of lack of surrounding soft tissues, all but the smallest defects require free tissue transfer. By definition in extensive extremity injuries, type IIIb and IIIc in the Gustilo classification, local tissues are not available.[26]

The reconstructive requirements of the heel and foot are similar. Both coverage and durable weight bearing surface with protective sensation should be provided whenever possible. Again local sensory tissues, such as plantar flaps, the dorsalis pedis flap and the lateral calcaneal flap from the lateral aspect of the foot, are useful for limited tissue losses. Larger defects of the foot, may require free tissue transfer.[11,62] When similar injuries occur in the hand vascularized tissue is available from the foot,[55] but other donor sites must be used for the foot itself. There is no ideal tissue however for substitution of the specialized weight bearing surface in a completely satisfactory manner. Sensate fasciocutaneous flaps or muscle flaps with skin grafted surface have all been used with success.[56] Special footwear however, for protection of the transferred tissue, is always necessary.[68]

Free vascularized bone flaps are necessary for patients with segmental skeletal defects of the long bones or for segmental defects of the mandible, which frequently may be irradiated. Patients with defects longer that 6 cm do less well with cancellous bone grafting and the incidence of delayed healing and nonunion is common them. Vascularized bone flaps are a better choice for these patients; they avoid at the same time, particularly in the upper extremity, the awkward external fixation devices that are necessary for the Ilizarov bone transporting technique. The use of vascularized bone flaps for the treatment of aseptic necrosis of the femoral head has also proven invaluable.

Besides the obvious need for soft tissue coverage and skeletal reconstruction, another indication for free tissue transfer is the need to reanimate a paralyzed face [28] or to dynamically reconstruct an extremity by the transfer of free vascularized and neurotized muscle.[53] Thus, closure of the eyelids and restoration of a smile can now be achieved (Fig. 7.2).

Elbow flexion can be obtained by substituting the function of the biceps muscle in longstanding brachial plexus injuries. Flexion and extension of the digits may also be restored by free muscle transfer in patients with Volkman's ischemic contracture, severe avulsion injuries or extensive electrical burns. Similarly functional restoration

Fig. 7.1. A) Short below knee stump with exposed bone and lack of soft tissues.

of the extremities can be achieved following tumor extirpation. Careful selection of the recipient motor nerve is essential to the recovery of function of the transferred muscle.

In several occasions motor nerve reconstruction with long nerve grafts may be required, before the free tissue transfer.

In conclusion free tissue transfer has extended surgical abilities in many directions and in none more dramatically than in extremity salvage. The reliability of the method has been proven in clinical practice, with success rate > 95%, but it is 100% related to laboratory and clinical experience. Casual application of the method is not recommended.

Fig. 7.1. B) Construction of arteriovenous fistula with the use of the contralateral short saphenous vein to provide vascular access.

Choice of Free Flaps

Since the arrival of clinical microsurgery, reconstructive surgeons have reevaluated human anatomy, searching for vessels and tissues suitable for free tissue transfer. The nature of the defect and of the donor site must be considered in each case, in order to choose the most appropriate tissue for transfer.

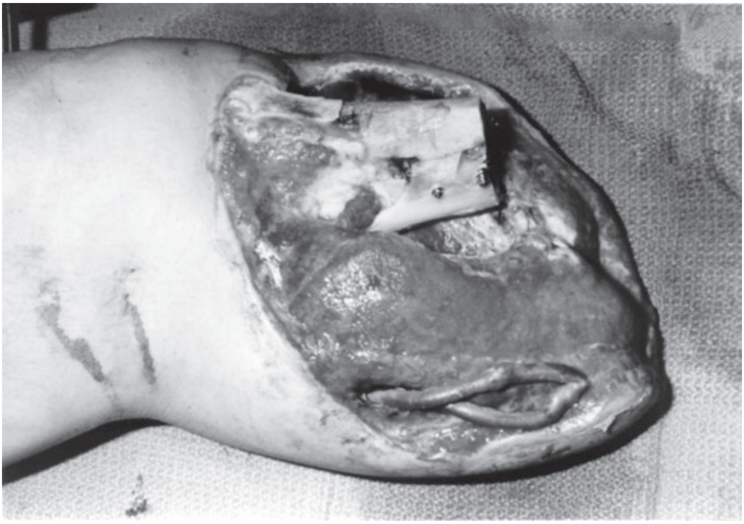

Fig. 7.1. C) A-V loop transposed anteriorly in the subcutaneous plane.

Fig. 7.1. D) Complete stump coverage with a free latissimus dorsi myocutaneous flap.

Fig. 7.1. E) The patient with his first below knee prosthesis.

A) Nature of the Defect

The shape and size of the defect and the texture of the surrounding tissues will influence the choice of the flap to be transferred particularly in face and hand reconstruction.

The degree of contamination or residual infection must be considered, because transfer of well vascularized tissue (muscle) may be required.

Sensibility or bone requirements must also be taken into consideration and finally, regional vessel accessibility for reestablishing circulation to the flap, may influence flap selection.

B) Nature of the Donor Site

Flap harvesting should not result in unacceptable loss of function or change in appearance (cosmesis) at the donor site.

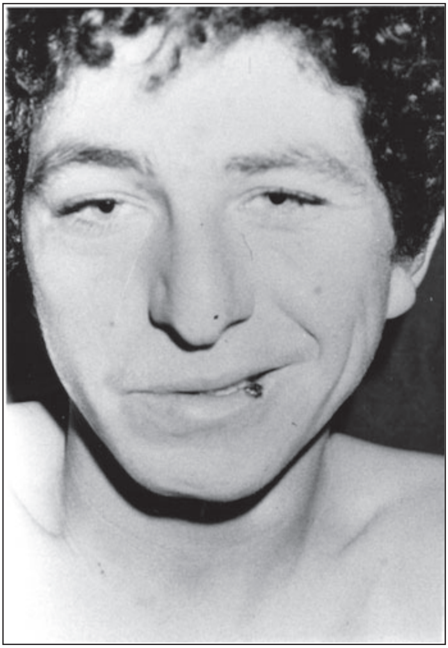

Fig. 7.2. A) Long standing postraumatic fascial paralysis. B), below. Functional muscle transfer to the face. Note the vascular anastomosis and the nerve coaptation.

Fig. 7.2. C and D) Postopeartively the patient in repose and smiling. Note the reformation of nasolabial fold.

Flap vascular pedicle should be carefully evaluated. The length of the pedicle and the status of the vessels are of great importance. Diseased vessels are not uncommonly found in diabetics and in patients with arteriosclerosis when flaps are taken from the lower part of the body, below the aortic bifurcation.

Ease of flap procurement and familiarity of the surgeon with flap dissection are two other factors that may influence the choice of the flap to be transferred.

Classification of Free Flaps

The following types of free flaps have been described: The fascial or fasciocutaneous, the muscle or musculocutaneous and recently the perforator flaps and the special tissues, such as vascularized bone, nerve, tendon, intestine, omentum, etc.

Fascial flaps consist of a circumscribed area of fascia. If the overlying skin and subcutaneous tissue is included, the flap is called fasciocutaneous. The vascular supply, usually a named artery, flows directly to these flaps and does not perforate muscle.

Fasciocutaneous flaps have the following advantages:

- Underlying vascularized bone such as segments of metatarsal, radius, scapula, or calvarium may be transferred with dorsalis pedis, radial forearm, scapular and temporal flaps respectively.
- Fasciocutaneous flaps tend to be less bulky than musculocutaneous flaps, a desirable characteristic for certain areas, as on the face, neck, hand and wrist, foot, etc.
- Several fasciocutaneous flaps may include a sensory nerve supply, important for hand and weight bearing areas of the foot reconstruction.

Fasciocutaneous flaps have the following disadvantages:

- Donor sites may be visible and objectionable, particularly if a skin graft is required for their closure.
- The vessel to the flap may be a large one (the radial artery for the radial forearm flap, for example) and its interruption may cause ischemic symptoms, or in the contrary it may be a small one, difficult to work with (deltoid flap).
- Fasciocutaneous flaps, unlike muscle flaps with skin grafted surfaces, change configuration with weight change.
- Fasciocutaneous flaps usually do not provide the bulk that muscle flaps do, and so may not be suitable for filling sizeable defects.

The most commonly used fasciocutaneous flaps are mentioned below:

- The *superficial temporal fascial flap*[8] supplied by the temporal artery is useful for reconstruction of small defects on the face, for resurfacing the dorsum of the hand and occasionally for reconstruction about the foot and heel where bulk is unnecessary. It is usually taken without the overlying scalp which is then closed over the donor site. The underlying outer table of the calvarium may be taken with the fascia as a vascularized bone graft. The donor site is acceptable.
- The *scapular flap*,[6,71] based on the circumscapular branch of the subscapular artery provides a very large segment of skin and soft tissues. The donor site is most commonly closed directly. Vascularized bone, the lateral edge of the scapula, may be elevated with this flap.
- The *deltoid flap*[18] vascularized through the posterior humeral circumflex vessels, includes the sensory branch of the axillary nerve and it can be used to restore protective sensation at the recipient site. The donor site may be objectionable, particularly if it cannot be closed without skin grafting.

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The *lateral arm flap*[44] supplied by the terminal branch of the profunda branchii artery is popular for coverage of hand defects. It is also a sensory flap if the lower lateral cutaneous nerve of the arm, branch of the radial nerve, is sutured to a sensory recipient nerve. The donor site is as acceptable as any in the upper extremity.

The *radial forearm flap* ("Chinese flap")[72] is based on the radial artery and the cephalic vein. A strut of the underlying radius may be taken with the flap. The ease of use, because of its large vessels, the relative thinness of the soft tissues and the possibility to restore sensation are its chief advantages. These advantages are offset by a very objectionable donor site unless direct closure is possible (skin expansion is occasionally indicated). The hairy skin in males is often undesirable and some circulatory impairment of the hand that necessarily results from the use of the radial artery. This may be severe or dangerous in the 20% of individuals in whom the superficial palmar arch is incomplete. A vein graft is required if the hand shows signs of vascular insufficiency. This flap is often used in head and neck, upper extremity and foot and ankle reconstruction.

The *groin flap*[60] based on the superficial circumflex iliac vessels was the first flap used for free tissue transfer in the lower extremity. It has small vessels that show considerable variation and make this transfer unreliable. The donor site is acceptable, The groin flap is still used occasionally and may be useful in skilled microsurgical hands, but there are better choices available today.

The *dorsalis pedis flap*[54,59] based on the dorsalis pedis artery is useful for defects where a thin sensory flap is needed. In addition it can be used without dividing the pedicle to cover the malleoli or, by releasing the extensor retinaculum, the anterior ankle and lower leg. The donor site tends to be troublesome (poor healing, poor take of skin grafts, inadequate protection of underlying structures). This flap should be used only under special circumstances.

The *first web space of the foot*,[55] based on the dorsalis pedis and the first dorsal metatarsal vessels, is excellent for sensate reconstruction of the hand and digits because of the similarity of the tissues. It is occasionally used for small defects about the foot.[25]

Muscle Flaps

Nearly any muscle will serve as a free flap if its vessel is large enough to permit microsurgical transfer. A type I vascular pattern (a single, large dominant vessel) is preferred. The transferred muscle should be easily spared and its use should result in only minimal functional impairment.

Muscle flaps used for free tissue transfer have the following advantages:

The donor site is usually both cosmetically and functionally acceptable. Endoscopic dissection of the muscle may minimize even further the donor site scar. Skin grafted muscle flaps tend to be "self-contouring", that is, the denervated muscle loses its initial bulk and often takes the contour of the area where it is transferred. Cosmetic results tend to be good. Skin grafted muscle does not change in size as the patient gains or loses weight, as occurs with fasciocutaneous, musculocutaneous and perforator flaps.

The rich circulation in muscle flaps permits their use in less than optimal recipient sites, (osteomyelitic defects, irradiated areas etc.).

Innervated transferred muscle can restore motor function (most applicable in the arm and in the face).[53]

It is possible to obtain long pedicles, particularly with the rectus abdominis and the latissimus dorsi muscles.

Muscle flaps may have the following disadvantages:

There is inevitable diminution of motor power of the functions served by the muscle. Practically this seems not to be of great importance.

There is inevitably some loss of normal contour and support at the donor site. Again, clinically this is usually not particularly troublesome. In an attempt to completely eliminate these disadvantages the perforator flaps have been described. The perforating branches of the vascular pedicle are dissected through the muscle which is then left in place while the overlying skin and subcutaneous tissue are elevated along with the vascular pedicle and used as free tissue transfer.[2,17,42,43,78]

The following muscles are most commonly used for free flap transfer:

The *latissimus dorsi muscle*[5,71] is the single most useful muscle. Its large size allows coverage of almost any type of defect. Alternatively, the muscle can be split, the lateral portion of it can be transferred to cover small defects, leaving the medial portion and its innervation intact.[21] The thoracodorsal branch of the subscapular vessel—the largest branch of the axillary artery—supplies the latissimus. The pedicle may be very long if the dissection includes the main subscapular vessels as far as the axillary artery. The donor site and its scar are acceptable. A drawback of the latissimus flap is that the patient sometimes must be turned on the operating table.

The *rectus abdominis*[9,10] supplied by the large deep inferior epigastric vessels is a long muscle, if taken from its origin on the chest wall to its insertion on the symphysis pubis and it is most easily obtained in the supine position, while the preparation of the recipient site is carried out simultaneously. The donor site scar is that of any vertical abdominal incision and as such is acceptable. The single greatest drawback to its use is the occasional complication of abdominal wall weakness or herniation that can be avoided with careful wound closure.[32] Reinforcement of the rectus fascia with synthetic mesh is sometimes indicated. Alternatively perforator flaps based on the deep inferior epigastric vessels can be dissected, sparing the rectus muscle completely and utilizing the skin and subcutaneous tissue of the lower abdomen (Fig. 7.3). The visible tendinous inscriptions are a minor disadvantage when the rectus muscle is used. These tend to fade as the muscle atrophies, but usually do persist to some extent.

The *gracilis muscle*[28] is commonly used for covering small defects and for functional reconstruction of the face or the upper extremity. Although this muscle has a segmental blood supply there is one constant dominant branch

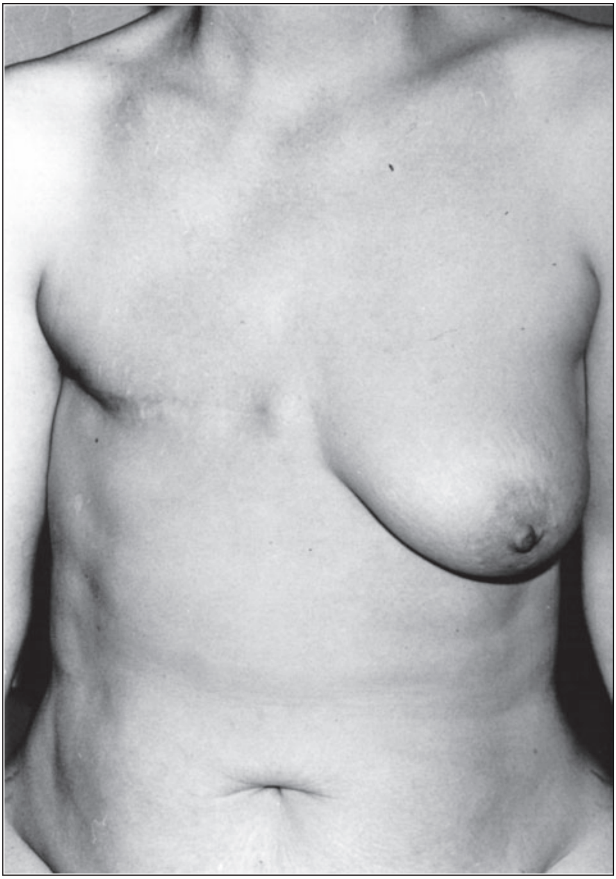


Fig. 7.3. A) Postmastectomy.

of the profundus femoris that arises 8-10 cm below its origin on the inferior pubic ramus. The pedicle, if followed back to the profundus femoris vessels, is about 6 cm long, but its vessels tend to be small. Because of its easy access and the inconspicuous donor site the use of this muscle is recommended.

Other muscle or musculocutaneous flaps, the serratus anterior, the gluteus maximus, the tensor fascia lata, the pectoralis minor or the extensor digitorum brevis from the foot, have all been used successfully in special circumstances.

Free Vascularized Bone

One of the most complex problems in reconstructive surgery is restoration of a bony defect. Nonvascularized bone grafting is generally used for bridging short traumatic defects or defects secondary to fibrous nonunion, bony absorption, or

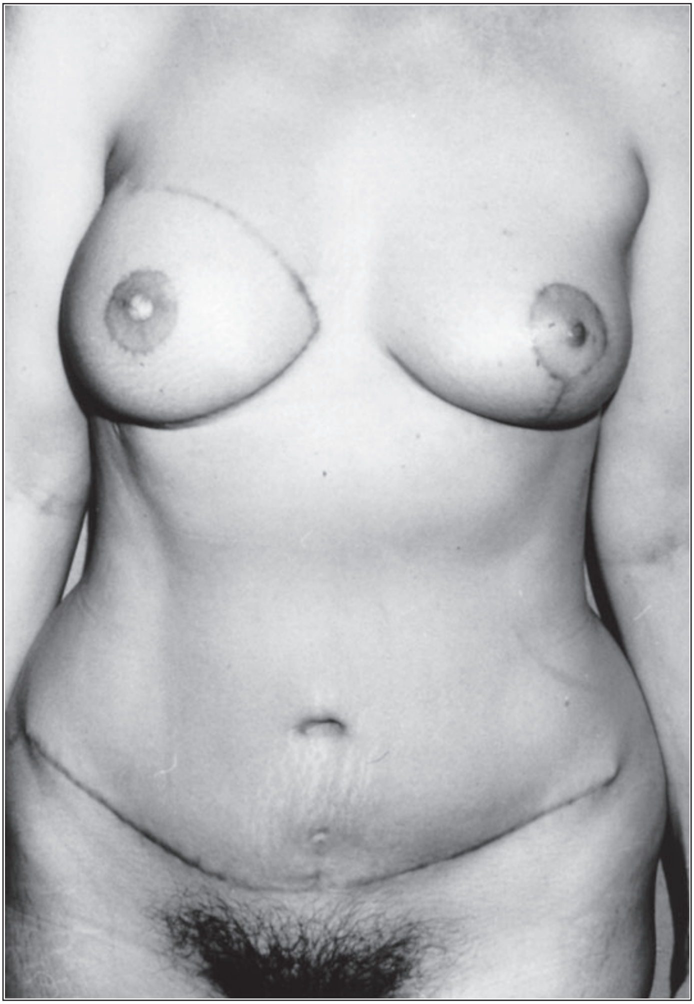


Fig. 7.3. B) Reconstruction of right breast with a free TRAM flap.

resection. For longer defects, however, free vascularized bone flaps are indicated. These, unlike nonvascularized bone grafts, remain viable; their blood supply is through the nutrient vessels. Bone healing occurs at a rate comparable to that of normal bone, creeping substitution does not occur and the quality of the recipient bed does not influence their survival.

Many vascularized bone grafts have been described as a component of fascial or fasciocutaneous flaps. Free rib flaps have also been described. None of these are good choices for extremity[92] or mandibular reconstruction; all are too small to be useful except possibly in the forefoot or the hand. The most frequently used vascularized bone flaps are: the iliac crest flap and the fibula flap.

The *iliac crest free flap*[73,82,83] is based on the deep circumflex branch of the iliac artery. Bone only or bone with overlying skin and subcutaneous tissue may be included, depending on the requirements at the recipient site. Experience, is mandatory for the elevation of this flap, (Fig. 7.4). The vasculature is reliable, but problems, mentioned previously, with flaps whose vessels originate from below the aortic bifurcation in arteriosclerotic patients, may be encountered. The major problem with using this flap is that the bone is inadequate, both in shape and volume, for replacement of defects longer than 10 cm. Longer defects are probably best bridged with vascularized bone flaps of sufficient length and suitable shape, namely the *fibula* flap[20,90] based on the peroneal artery. This artery, like the radial artery in the radial forearm flap, is a large vessel in transit to the distal limb. It may be used not only as the circulatory supply for the fibula flap, but also as a "flow through" vessel to replace a damaged segment of artery. The flap, besides the bone, may incorporate muscle up to half of the soleus or a cutaneous component, or both, to provide soft tissue coverage if the defect is of moderate size. Up to 25 cm of fibula may be taken, depending on the patient's body habitus. If the flap is used in the lower extremity, the bone is then telescoped into the medullary cavities of the tibia or femur. This added requirement means that the bone must be at least 5 cm longer than the defect.

There is no significant donor limb morbidity. It is necessary to be cautious in dissecting the upper end, to avoid damage to the common peroneal nerve, and at the lower end to leave enough length of distal fibula to retain ankle stability (8 cms) Exercise of a normal degree of surgical care, including hemostasis and suction drain-

Fig. 7.4. A) Extensive squamous cell carcinoma of the anterior mouth floor with mandibular involvment.

Fig. 7.4. B) Extensive resection of the anterior floor of the mouth and mandible (angle to angle) with bilateral neck dissection.

age, should prevent postoperative problems. Osteotomy of the flap, in order to obtain double barrel configuration for femur replacement or in order to provide the desired shape for mandibular reconstruction, is feasible.

Healing is rapid with the prompt appearance of callus at about 2 months in adults. The bone undergoes compensatory hypertrophy with stress. Unassisted weight bearing is usually possible by 15 months. It is not unusual for stress fractures to appear after initiating weight bearing, but these stabilize and heal quickly with immobilization, usually within 4-6 weeks. Some patients may require additional cancellous bone grafting if delayed union occurs, as it sometimes does at the distant junction of the tibia with the vascularized bone graft (17% in Weiland series).[89]

In summary, fasciocutaneous, muscle, or perforator flaps have advantages and disadvantages and the reconstructive surgeon should feel comfortable working with all types. The versatility of the vascularized fibula makes it very useful as a living bone flap for segmental bony defects of any significant length. Finally replacement of both soft tissues and bone in one stage, results in the salvage of limbs that would otherwise be lost or would require a protracted reconstructive course and allows the functional reconstruction of the face following severe trauma or tumor extirpation.

Therapeutic Considerations

In treating extremity trauma with extensive soft tissue injury one cannot overemphasize the need for and the importance of vigorous initial debridement. All tissues of questionable viability including bone should be excised to viable margins. This is the single most important step in treatment, yet it is the most often neglected. Serial re-exploration and debridement are carried out every 24-48 hours,

Fig. 7.4. C) Design of the iliac crest fasciocutaneous flap.

usually under general anesthesia, until the wound is clean and stable. Wounds managed with this aggressive approach are usually ready for definitive coverage within the first week. A final debridement back to normal tissue is performed when the wound is covered, allowing normal healing between the wound and the free flap interface.

Timing of Coverage

Many have written on the optimal timing of free tissue transfer. It has been proven by large series of free flap coverage of extremity defects that the morbidity, infection, number of flap failures, time for bone healing, number of operative procedures and length of hospital stay all rise precipitously if wound coverage is delayed beyond the early stage when there is no tissue fibrosis or tendency for vascular

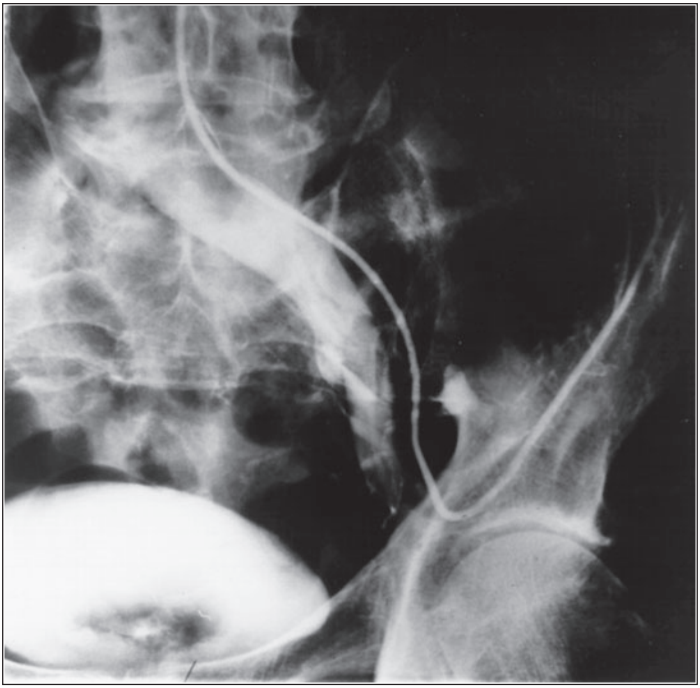


Fig. 7.4. D) Arteriography demonstrating the deep circumflex iliac artery.

spasm.[12,22] The question of timing can be best summed up by simply saying that coverage should be carried as soon as a wound is suitably receptive and as soon as the patient's condition will permit the procedure. There are special circumstances, however, in traumatic coverage, such as exposed major vessels and nerves, that require acute free tissue transfer 'emergency free flap', that is within 24 hours from the time of injury.[94] If a free flap is used for reconstruction following tumor removal, the transfer is usually performed simultaneously with the extirpating surgery.

The Recipient Site Vasculature

Free flap circulation is usually reestablished by direct anastomosis to regional arteries and their companion veins. These are most often exposed through an incision proximal to, yet connected with the defect. The vessels are followed from proximal to the zone of injury until any vascular damage is noted and avoided. The proper site for the anastomosis to undamaged vessels can then be selected. In extremity reconstruction occasionally distal exposure is possible for "upside down" flap placement if both arterial and venous flow are normal.

Preoperative angiography is sometimes indicated to define vascular anatomy. Adverse effects from angiography have occasionally been noted[93] and therefore it is preferable to avoid angiography within 24 hours of a planned free flap transfer to

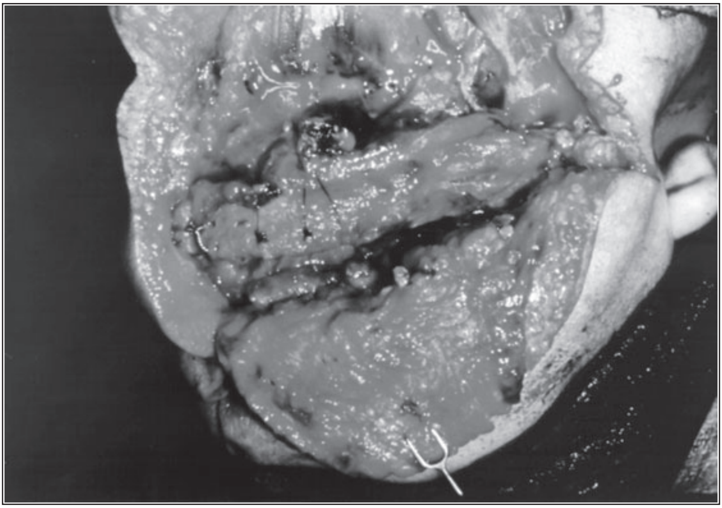


Fig. 7.4. E) Mandibular and floor of mouth reconstruction with the iliac crest free flap.

allow any inflammation and spasm of vessel walls, induced by the procedure, to subside prior to the operation.

It is preferable to connect the vessels of the free flap to the regional vessels using end-to-side anastomosis.[23] This has the advantage of preserving distal blood supply and avoids problems associated with anastomosing vessels of different diameter. Simple linear slit arteriotomy is usually used, although excision of an elliptical portion of the vessel wall may make anastomosis easier in large thick walled vessels or in those with calcified or atherosclerotic walls. Excision of vein wall is almost never indicated (Fig. 7.5). End-to-end anastomosis is occasionally useful, particularly for damaged vessels with no distal run off. No difference has been noted between any of these different techniques nor is there any experimental evidence that there is any advantage of one over the other.

There is often-unjustified-concern about the "single vessel leg". An end-to-side anastomosis can always be done safely in these legs, but it should not be done within the zone of injury because dissection is difficult, the vessels are friable and thrombosed veins are commonly encountered.

In extremities where a bypass vein graft has been used to restore circulation it is sometimes possible to use the bypass graft immediately, before scarring develops, for free flap circulatory attachment.

The choice of which vein to use for free flap drainage may be a difficult one. The deep companion veins are often thrombosed in severely traumatized extremities. It is then best to use a superficial vein for free flap venous drainage. For this reason when large superficial veins are encountered during the initial incision they should be preserved. In the lower extremity it is also sometimes possible to mobilize either the long or the short saphenous vein leaving the upper end in situ. The thick-walled

Fig. 7.4. F) Bone scan demonstrating viability of the transferred osseous flap.

long saphenous vein, however, may develop prolonged spasm which can compromise venous outflow.

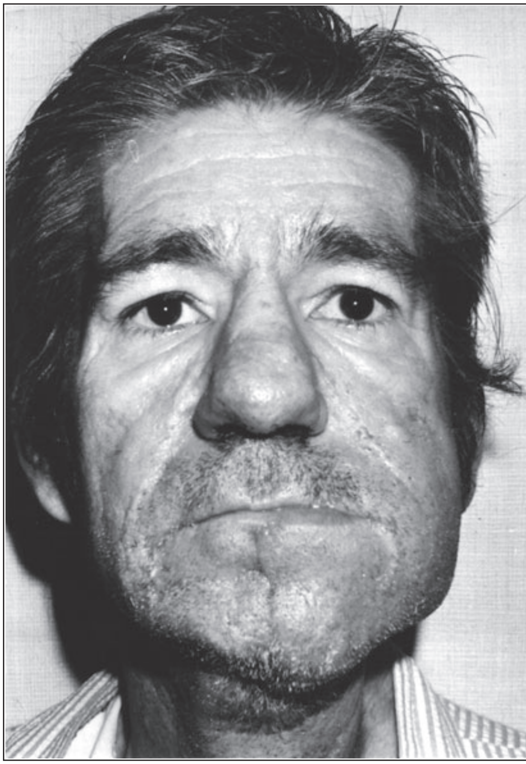
Heparin solution (5000 units in 100 cc of saline) and vasodilating solutions (Xylocaine) are used during surgery to clear the vessels ends and to prevent spasm.

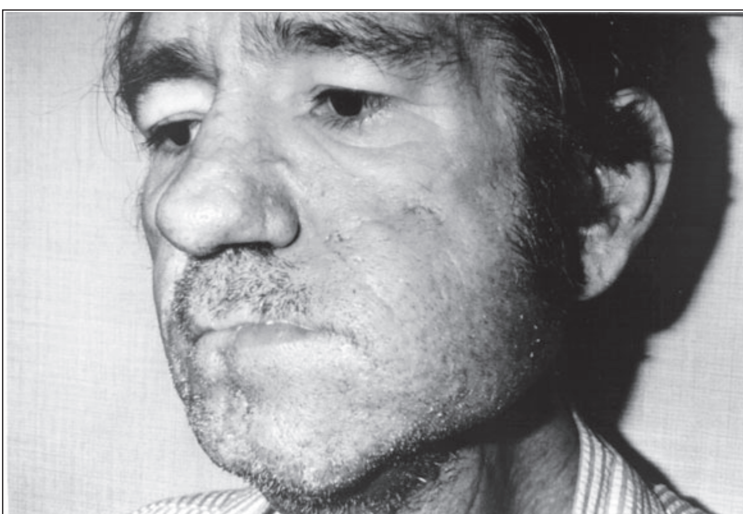
Vein Grafts

When direct circulatory access for free flap reconstruction is difficult or impossible, vein grafts may provide free flap circulation. In the lower extremity the short saphenous vein[87] has many attributes, which make it ideal for use, when vascular access is not available and long vein grafts are needed. These include:

1. Sufficient length of 40-50 cm depending on patient habitus. This length may be used to serve as a direct arterial graft from higher up on the limb, while local veins are used for flap drainage, or the long vein graft may be doubled into an A-V loop to provide both arterial and venous components (Fig. 7.6).

Fig. 7.4. G, right, and H, below) Postoperative appearance. Note normal contour of the chin.





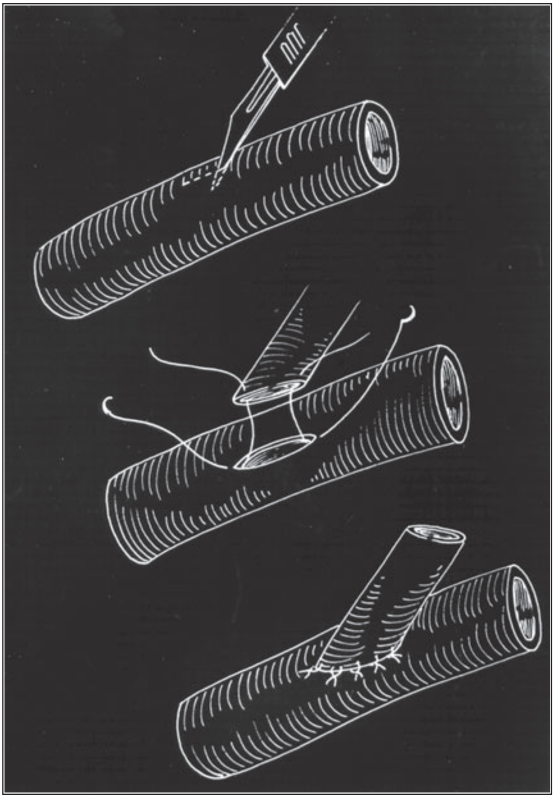


Fig. 7.5. Linear slit arteriotomy for end to side anastomosis.

2. The short saphenous vein is thin-walled in comparison with the long saphenous vein, usually has a nearly constant diameter throughout its length and presents no problems with direct end-to-end anastomosis with the vessels of most transferred flaps.
3. The vein most of the time may be left in situ at its upper end. This reduces the amount of dissection necessary, avoids one anastomosis and provides double drainage into both the superficial saphenous system and the deep popliteal and femoral systems. This is of importance in patients who have impaired outflow secondary to deep venous thrombosis or obstruction.
4. Flexibility of vein graft permits placement of free flaps where desired, independently of the length of the free flap vascular pedicle and of the condition of regional vessels.
5. The separated vein graft components permit accurate separable ultrasonic Doppler monitoring of both the artery and the vein and so should give prompt warning of venous occlusion—the usual cause of free flap loss.

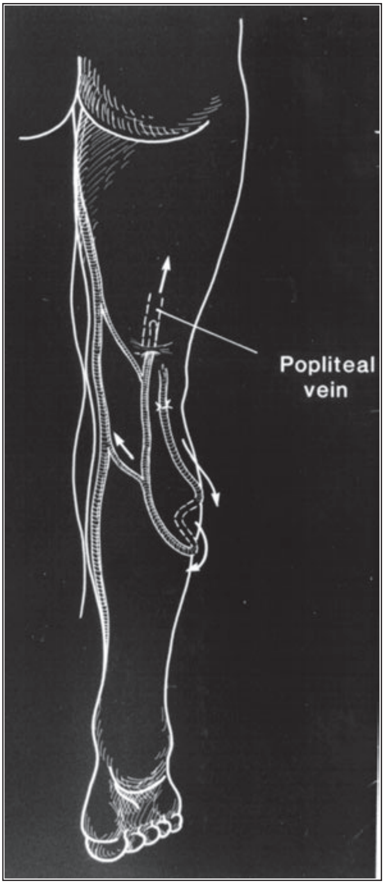


Fig. 7.6. Short saphenous vein A-V loop.

The use of temporary arteriovenous fistula has the advantage of providing continuous flow through the graft until the free flap is in place and ready to have its circulation restored with end-to-end anastomoses. Cessation of flow then should be brief. The flexibility of short saphenous vein grafts for complicated free flap reconstructive procedures in the lower extremity is impressive. The long saphenous vein is also useful when a free flap is needed in the thigh or lower abdomen. Its upper end may be left intact at the fossa ovalis and the lower end anastomosed to the femoral artery or to one of its branches setting up a temporary A-V fistula.[16]

Flap survival is not related to the use or the length of vein grafts, but rather to the severity of the condition responsible for the tissue defect.

Postoperative Management and Complications

Antibiotics

All patients undergoing free tissue transfer reconstruction either for trauma or disease are placed on appropriate antibiotic therapy. It should be noted, however, that antibiotic therapy is not a substitute for proper wound care, adequate surgical debridement and gentle tissue handling.

Anticoagulants[37]

Technical error including inadequate vessel anastomoses, inappropriate selection of recipient vessels, pedicle kink, twist or tension and compression from wound closure, are the most common causes of anastomotic clotting. Occasionally, other factors, such as a true hypercoagulable state in patients with multiple injuries may be present.[49] There is no unanimous agreement among microsurgeons about the anticoagulant regimen to be followed because of absence of complete data about the antithrombotic power of each anticoagulant.

Heparin inhibits fibrin formation, which is needed for platelet adhesiveness, by binding to antithrombin III and inactivating thrombin. Thrombin bound to the vessel wall, however, may be resistant to heparin and this may be responsible for the occasional failure of the prophylactic administration of systemic heparin. Topical administration of heparin may be more effective and avoids bleeding complications from donor and recipient site.[57]

For inhibition of thrombus formation an antiplatelet drug is also needed. *Aspirin* by preventing the production of postaglandins reduces the production of thromboxane A_2, which is an aggregant and vasoconstrictor agent, that affects not only the anastomosis itself, but also the downstream flap circulation. The role of aspirin on the microsurgical anastomosis is not completely defined, but clinically seems to be effective. Its use should be omitted in debilitated patients and where potential bleeding may be detrimental, such as in intracranial reconstruction.

Dextran[29] of low molecular weight (40.000 MW) in 10% solution has been used in microsurgery as a pharmacologic adjunct because it is a volume expander, increases blood flow, interferes with platelet attachment to vessel wall and it has antifibrin function. It may be dangerous however, because of allergic reactions and tissue edema, including cerebral and pulmonary edema.

Occasionally *fibrinolysins*[14,50]—streptokinase, urokinase and recombinant human tissue-type plasminogen activator (rt-Pa)—may be useful in salvaging a failing free flap, by local infusion. If however the problem is anastomotic clotting, reanastomosis should always be done. Prophylactic local infusion of recombinant human tissue type plasminogen activator has been proven effective in experimental setting.[3,51,52] Its use appears to be safer, because of its unique ability to electively activate the fibrinolytic system only at the site of fibrin presence. This localized thrombolytic effect does not deplete clotting proteins and diminishes the risk for hemorrhagic complications.

Other substances such as recombinant hirudin, which is contained in leech saliva and inactivates thrombin in the absence of antithrombin III, monoclonal antibodies against platelet adhesion receptors and substances that inhibit the coagulation pathway, are under investigation.

In conclusion, each team has established its own practice but routine postoperative use of full anticoagulation, except in complicated situations, is discouraged. We prefer to administer one intravenous bolus of heparin (5000 units in adults) at the time of completion of the anastomoses (the 30 minutes following opening of the anastomosis are the most critical for clot formation) and one aspirin per day postoperatively for 3 weeks.

Patients undergoing elective reconstruction may be started on aspirin preoperatively. Recently, severely injured or bedridden patients are kept on low molecular weight heparins. Anticoagulant substances must be used judiciously, because they may cause bleeding and wound hematomas that may adversely effect the surgical outcome.

Free Flap Monitoring

Monitoring of the patency of microvascular anastomoses, tissue perfusion and viability of free flaps is essential. In large series of free tissue transfers the re-exploration rate ranged from 6-25% with success rates, between 91% and 99%.[27,39,85,91] Therefore salvage of a large number of failing flaps is possible. Early warning of circulatory impairment and immediate return to the operating room are the most important elements in saving flaps in trouble. The ideal monitor should be a noninvasive, easy to use, inexpensive device that will measure tissue perfusion, will distinguish between arterial and venous flow, and will have an alarm activated by alteration in flow or perfusion. There is no ideal device. Several methods nevertheless, are effective and reliable in free flap monitoring.

Clinical evaluation includes assessment of appearance, capillary refill and temperature. It is useful only in the presence of a cutaneous element.

Temperature monitoring[40,48] with probes (either invasive or noninvasive) is attractive because of its simplicity, but it is not reliable enough. The patient's temperature, the ambient air temperature, dressings, bed covers, flap thickness, moisture evaporating from the flap's surface, all may influence surface temperature. If temperature monitoring is used, control sites should be carefully chosen—similar tissue and circumstances—and the probes should have been carefully calibrated. Because of these variables, there is not absolute value for temperature differential. Difference between differential surface temperature measurements at two points in time greater than 1.8°C is indicative of an ischemic event. Usually flap temperature of 32°C degrees or greater, suggest that the flap is healthy, readings of 30-32° are marginal, and temperatures of less than 30°C degrees suggest failing circulation and vascular problems. Both arterial and venous occlusion lead to a fall in surface temperature. Acland found a temperature response to vessel occlusion to occur in less than 1 minute and confirmed this intraoperatively.[1]

$p0_2$ monitoring[30,31,34] is another method that may provide useful information on the circulatory status of a free flap. The probe is taped to the skin over a film of distilled water or it may be implanted for monitoring of "buried" flaps. The transcutaneous $p0_2$ measurement may be affected by the composition of inhaled gasses, or pre-existing pulmonary disease. The normal peripheral skin reading, for a patient breathing room air, is usually 70-80 mmHg. A free flap with $p0_2$ of greater than 25 mmHg. will usually survive. Transcutaneous $p0_2$ readings are often elevated during the first 48 hours postoperatively, possibly the result of sympathectomy. As with

temperature monitoring, the comparison of relative changes in pO_2 levels over time is more important than absolute pO_2 values.

Photoplethysmography[31,75,88] is able to indirectly detect blood flow only in the superficial layers of the skin and therefore is not suitable for buried flaps. It makes use of the transillumination of the skin. Infrared light will penetrate 3 mm below the surface of a flap and some of this will be reflected back from the red cell mass. The absorption coefficient of blood is different from that of connective tissue and therefore pulsatile changes in tissue blood volume produce a corresponding change in the amount of reflected light. The waveform produced is charted.

Fluorescein,[31,39] a vital dye given in conventional doses, (10-15 mg/kg) provides accurate, one time only, measurements of flow. Serial quantitative skin fluorescence measurements following serial intravenous administration of low-dose fluorescein dye (1.5 mg/kg) have been used experimentally, but are intermittent and require the presence of a skin island. Therefore it has little usefulness for continuous clinical free flap monitoring.

Radioactive isotopes[31,39] are used for detection of the viability of buried vascularized bone transfers, but have the same limitations as the vital dye, of one time measurement.

Electromagnetic flowmetry[31,39] is based on the principle that a column of blood in a vessel acts as a moving electrical conductor generating an electric potential as it passes at right angles through the field created by an electromagnetic flow probe. The strength of this potential is proportional to the velocity of flow. This electric signal is processed and amplified by the flowmeter and a reading is displayed, expressed in milliliters of flow per minute. Although the method may give accurate flow measurements, it is invasive and not practical for clinical use.

The *laser Doppler capillary perfusion monitor*[38,95] is an application of low-power laser technology designed to provide noninvasive continuous monitoring of blood flow through the skin or other tissues. It makes use of the Doppler principle to monitor perfusion of red blood cells in the microcirculatory bed. This device works on the principle that the frequency of light, back scattered from moving red blood cells, shifts in proportion to the velocity of the moving cells. The flow calculation is dependent not only on the average velocity of the red cells, but also the density of red cells in the measured volume.

The absorption and the reflection characteristics of the skin control the depth of light penetration; this varies from 0.6-1.5 mm (the darker the skin the lesser the penetration). This limited penetration avoids the influence of the major vessels and assures that the signal is derived from the microvascular system.

Although the laser Doppler has gained popularity recently as a noninvasive method for measurement of tissue perfusion it has certain significant limitations in clinical practice, because it does not provide an absolute quantitative measurement of blood flow, but rather the trend of perfusion values must be followed. Further as it depends on the density of red cells, it is not adequately sensitive in anemia or hemodilution, a fairly common state in free flap surgery. The laser Doppler seems better suited for experimental, rather than clinical monitoring of the microcirculation.

The *high frequency (20 MHz) ultrasonic Doppler*[65,66,80] in a pulsed mode measures blood flow in small arteries using a 1 mm piezoelectric crystal which emits alternate pulses of ultrasound and, in the interval time between emitting, functions as a receiver.

The frequency of the reflected sound, directed at a moving column of blood within an artery, is shifted. This converts the electricity to ultrasound. A silastic cuff encircles the crystal, this is secured over the vessel with fine 10-0 sutures to prevent dislodgment. Meticulous placement during surgery at 45° to the arterial wall is essential because postoperative adjustments are not possible. The wires exit the wound and are then sutured to the skin. By placing the cuff distal to the arterial anastomosis, continuous direct monitoring of the blood flow is possible and arterial occlusion is detected almost immediately. Venous obstruction produces an increase in the amplitude of the waveform tracing. After a week the probe is removed percutaneously by gentle traction. The device provides direct monitoring and it is valuable for monitoring buried flaps.

Although some of the more sophisticated instruments described above have the capability of measuring blood flow directly, in clinical practice the conventional *ultrasound Doppler*[4] device is adequate. This instrument makes use of continuous wave ultrasound, usually in a range between 5-10 MHz. It is the most practical noninvasive method for monitoring blood flow. It is inexpensive and readily available. It requires experience to interpret the audio output, but this is easily obtained and the differences between arterial and venous flow is usually apparent. The former is high pitched, shrill and sharply pulsatile. The venous signal is low pitched, varies with respiration and is less pulsatile. The venous signal is a background noise which is harder to distinguish, but once learned it is easy to hear. One must be careful to detect it, because it is possible to be deceived by a continuing arterial sound despite complete venous occlusion. In addition the device cannot be used for a deeply "buried" free flap and interpretation of the sounds may be difficult in the free tissue transfers in the head and neck because of the proximity of the carotid artery and jugular vein. The ultrasonic Doppler is a valuable adjunct for postoperative monitoring.

The Tandem Doppler Probe[86] an implantable Doppler device compares the pre- and postanastomotic waveforms simultaneously and allows for quantitative detection of anastomotic narrowing of as little as 5%. It may accurately identify subtle pathologic anastomotic waveform changes in blood vessels smaller than 1 mm. and it is useful for objective assessment of the technical adequacy of the anastomoses intraoperatively and during the postoperative period.

Near-infrared spectroscopy[84] provides a sensitive and reliable method for rapid detection of changes in tissue oxygenation, hemoglobin oxygenation and blood volume in a flap. It can accurately identify arterial or venous occlusion even in "buried" flap. It is unaffected by light, portable and easy to use.

In conclusion free tissue transfer is a reliable reconstructive method that requires aggressive preparation of the recipient site, careful selection of the donor tissue, faultless execution of the anastomoses and precise postoperative management.[41] The results are usually gratifying and worth the effort for the patient and the treating surgeon.

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7

Free Flaps

Lior Heller, L. Scott Levin

Introduction

Autologous tissue transplantation describes the surgical technique to transfer tissue from one location in the body to another using the operating microscope and techniques of microvascular surgery to perform small vessel anastomoses.

Reconstructive microsurgery began more than three decades ago with the introduction of the operating microscope for anastomosis of blood vessels, described by Jacobson and Suarez.[1] Beginning with microsurgical repair of digital arteries and digital replantation in the 1960s[2,3] microsurgical composite tissue transplantation began in the 1970s. Microsurgeons expanded their efforts from achieving tissue survival to include the improvement of function as well as appearance in the 1980s. In the 1990s, the emphasis has shifted to outcome. Today, composite transplantation or free tissue transfer routinely provides not only coverage but facilitates function.

Microsurgical reconstructive procedures became an integral part of almost all the surgical fields. For example, in orthopedics, the simultaneous management of fractures and associated soft-tissue injury the so-called "orthoplastic approach" is now accepted treatment for extremity trauma. It allows for optimal repair processes to take place for bone and soft tissue while avoiding the adverse sequelae of failed fixation, sepsis, and ultimately amputation.

Free flaps include isolated transfer, composite tissue transfer, and functioning free muscle transfer. Structural transfers such as vascularized bone grafts or toe transplantation for hand reconstruction as well as specific tissue transfers such as vascular and neural grafts are also an integral part of the microsurgical reconstruction armamentarium. While such "grafts" do not involve large amounts of tissue, it is considered tissue transplantation and thus is included as a free tissue transfer. In this Chapter we will concentrate on the most common flaps used for reconstruction.

Free tissue transfer procedures are by nature technically complex. This is due in part to the fact that no two reconstructive cases are exactly alike. The surgical solution tends to vary from case to case in the location, amount, and types of tissue that need to be replaced. Another distinguishing characteristic is that free flap reconstruction is a three-dimensional process that requires considerable preoperative planning. The best donor site must be chosen and the flap precisely designed so that it fulfills the needs at the recipient site.

Selection of Tissue Transplantation

Free flaps can be categorized into two different types of transplants. Isolated tissue transplants include skin, fascia, muscle and bone. More commonly "composite

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tissue transplant" represents a more complex flap and provide more than one function. Examples include myocutaneous, osteocutaneous, or innervated myocutaneous flaps. Flaps that include bones are described in an other Chapter in this book.

Determining the type of tissue deficiency and surface requirements will determine the type of flap to be selected. Tissue transplants are selected with respect to recipient site requirements, vascular pedicle length, donor site morbidity and anticipated aesthetic result. For example, a myocutaneous latissimus dorsi flap would not be transplanted to the dorsum of the foot due to its bulk and the fact that the donor tissue does not match the dorsum of the foot. Other flaps such, as an isolated skin flap (radial forearm flap or lateral arm flap) would be considered a better transplant. Similarly, to fill dead space after sequestrectomy of an infected tibia, a lateral arm flap, which is a small skin flap of approximately 5 x 7 cm would not be selected, due to its lack of bulk and the fact that the muscle flaps, rather than skin flaps are known to be more effective in treatment of osteomyelitis. The use of a skin paddle with composite tissue transfers can be done for either contouring or as a monitor for perfusion of the flap.

The next consideration is whether or not dead space needs to be filled. If a flap would be used purely for resurfacing, such as on the dorsum of the hand so that secondary tendon reconstruction can be performed, a large bulky flap would not be required. However, if there is significant dead space, a large muscle flap such as a latissimus dorsi flap should be considered. Osseous flaps are selected for structural defects such as intercalary bone defects resulting from trauma, tumor, or infection. If a vascularized bone flap is to be selected, the cross section of the bone defect, available vascular supply, and fixation of the vascularized bone graft must be taken into consideration.

Not all flaps are selected to replace missing tissue. There are instances where tissue coverage exists but is insufficient in texture or quality. A soft tissue envelope may need to be augmented such as using a scapular flap to resurface a knee with unstable kind as a first stage before a total knee replacement. There are free flaps that are performed for purely aesthetic reasons such as the resurfacing of extremities. This is an unusual use of free tissue transfer and it is only used in special cases. A combination of the above selection factors is what determines free flap selection.

Timing of Free Tissue Transfer

The timing of the wound closure using microsurgical techniques is important. In severe injuries of the lower extremity with associated soft tissue defects, early aggressive wound debridement and soft tissue coverage with a free flap within five days was found to reduce postoperative infection, decrease flap failure, nonunion and chronic osteomyelitis.[4,5] Godina emphasized the pathophysiology of the high-energy trauma and the emergency (during the first operation) or the importance of radical debridment and early tissue coverage within the first 72 hours.[6]

Lister and Scheker reported the first case of an emergency free flap transfer to the upper extremity in 1988, and they defined the emergency free flap as a "flap transfer performed either at the end of primary debridment or within 24 hours after the injury".[7] Yaremchuk recommended that flaps should be transferred between 7-14 days after injury and several debridements. The argument in favor of this approach is that the zone of injury, which often may not be apparent at presentation, can be determined by serial debridements performed in the operating room over several days.[8]

When deciding to perform a primary closure with a free flap two keys factors should be considered; the presence of an exposed vital structure and the risk of infection. A vital structure is defined as "one that will rapidly necrose if not covered by adequate soft tissue."[9] The decision of what constitutes a vital structure depends on circumstances. Tissues such as vessels, nerves, joint surfaces, tendons and bone denuded of periosteum, may lose function and may create an environment resulting in infection when left exposed for long periods of time. In the decision-making process, the surgeon must consider the risk of leaving the vital structure exposed, its functional importance, and the probability of differential recovery of function considering primary or delayed primary coverage.

The risk of infection is the second important factor that should be considered, because it may jeopardize the quality of the functional recovery or the free flap. As the risk of infection increases, the wisdom of primary closure with a free flap is reduced. Debridement of the wound is the most powerful surgical tool to reduce the risk of infection of the wound. If radical debridement is not possible, it is not considered safe to perform a primary free flap transfer. Another perspective is that the capability to perform free tissue transfer allows the surgeon increased freedom to proceed with radical debridement and may actually reduce the risk of infection.[10] Factors such as the mechanism of injury, the elapsed time and the degree of contamination of the wound should be considered in order to better evaluate the degree of wound infection. In an acute, sharp noncontaminated injury, when closure would be routinely performed if there were no skin loss, there seems to be little reason not to consider an emergency free flap.

There is more than one classification of flaps. The flap may be named after the first describing author, or it may be named according to several anatomical features, including the type or name of the tissue(s) (skin, muscle, musculocutaneous, fasciocutaneous), the location from where it is harvested (anterior lateral thigh), the type of vascularization (number of pedicles, septocutaneous, anterograde and retrograde flow) the name of the main feeding artery (dorsalis pedis flap), the shape of the flap (island flap), the origin of the flap (local versus distant flap) and way that are transplanted (free, microvascular flaps).

For practical use it seems best to divide muscle from fasciocutaneous flaps. We use classic flap terminology. Attention is focused on the few most useful free flaps with which most problems can be adequately solved.

Specific Tissue Transfer

The commonly used fasciocutaneous free flaps are the lateral arm flap, radial forearm flap, scapular flaps, dorsalis pedis and groin flaps.

Lateral Arm Flap

This flap can serve as innervated fasciocutaneous flap or as de-epithiliazed subcutaneous fascial flap. The lateral arm flap is based on the posterior radial collateral vessels (PRCA). The artery is a direct continuation of the deep brachial artery. The draining veins of this area are the venae comitants of the PRCA. The pedicle length is up to 7 cm. The external diameter of this artery is usually 1.5-2.0 mm but sometimes can be smaller, 0.8 mm. The vein's diameter ranges from 2.0-2.5 mm. The anatomy of this vascular pedicle is constant, in contrast with the medial arm flap, which has a more variable vascular supply.

The lateral arm flap is innervated by the posterior brachial cutaneous nerve, a proximal branch of the radial nerve (C5-6), giving the flap potential as a sensate flap. Additional sensory supply comes from the posterior antebrachial cutaneous nerve which divides at the distal upper arm, with the upper branch supplying the posterior inferior upper arm and the lower branch supplying the lateral side of the arm and elbow.[11]

The dimensions of the skin flap can be up to 8 x 15 cm. The surface markings that are important in planning include:

a. a line that joins the deltoid insertion with the lateral epycondyle (this line marks the lateral intermuscular septum and the course of the PRCA), and
b. design the flap with this line as the central vascular axis. The deep fascia is included in the flap, but it also can be harvested based on the PRCA pedicle alone, and this kind of flap can be advantageous in cases where thin well-vascularized coverage is required and for coverage of areas where tendon gliding is required.[12]

The distal territory is thin and is innervated by the lateral brachial cutaneous nerve of the arm, and is often hairless. In addition, vascularized bone (humerus) may be harvested with this flap for composite reconstruction[13] (Fig. 8.1).

The periostal blood supplying from the PRCA will allow a vascularized bony segment 10 cm long and 1 cm wide to be included with the skin flap.

Flap Harvesting

The patient position is supine, arm draped to allow free movement: lying on an arm table or fixed across the chest. A tourniquet is recommended but sometimes is difficult to maintain during proximal dissection. Dissection begins with a posterior incision to triceps muscle fascia. The flap is raised sub-fascially and skin is sutured to the fascia to prevent sheering. The posterior fascia is elevated exposing the lateral head of the triceps. Continue dissection to the anterior border of triceps muscle. Here the fascia dives deep and inserts into the humerus. Perforators are now seen in the septum. An anterior incision down to fascia is made. The anterior fascia over the brachialis and the brachio-radialis muscle is incised and follows the level of the periosteum of the humerus. The distal continuation of the PRCA is ligated. Separate the fascial septum as close as possible to the periosteum. The pedicle is followed proximally under the triceps muscle into the spiral groove. The lower cutaneous nerve is separated from the radial nerve. The flap elevation technique should be modified when the fasciocutaneous flap is designed to include vascularized bone (humerus) and tendon (triceps).

Radial Forearm Flap

This is a thin well-vascularized fasciocutaneous flap on the ventral aspect of the arm widely used in China before it was popularized in the Western literature.[14,15] The flap is based on the radial artery, which can achieve a 20 cm pedicle and has a diameter of 2.5 mm. This length of the pedicle facilitates the microsurgical anastomosis out of zone of injury. The venous drainage is through the venae

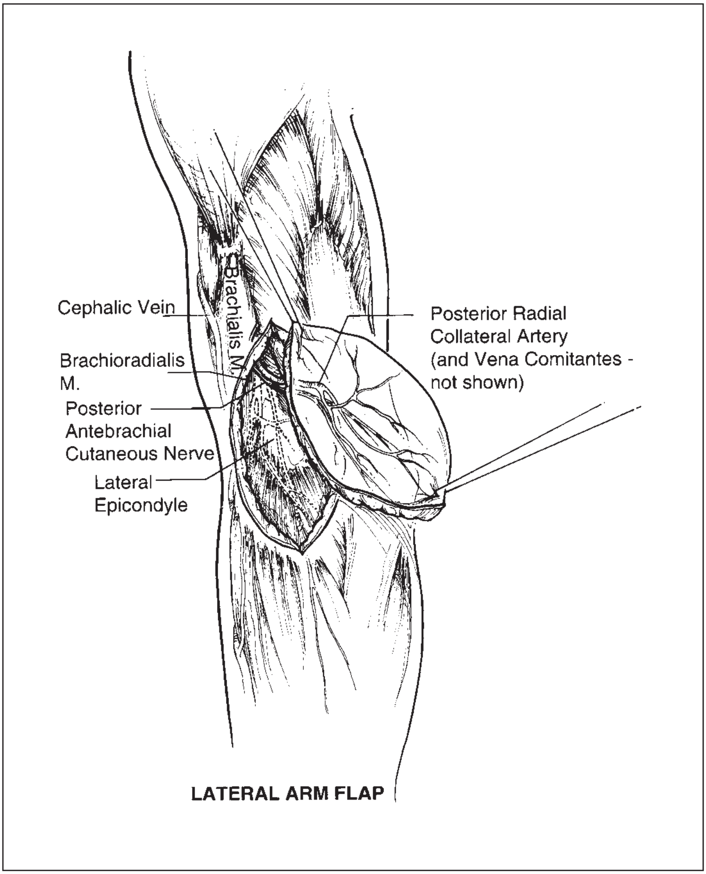

Fig. 8.1. Lateral arm flap

comitantes of the radial artery but the flap can include the cephalic vein, the basilic vein or both. The flap can contain the lateral antebrachial cutaneous nerve or the medial antebrachial cutaneous nerve and serve as a neurosensory flap. The size of the flap can be 10 x 40 cm^2. A portion of the radius can be included as a vascularized bone with this flap.[16] The advantages of this flap are: a long pedicle, and potential sensory inervation. The quality of the bone from the radius is mainly cortical and not of any substantial volume.[17] Including the bone in the radial forearm flap may lead to stress fractures.

Preliminary tissue expansion will increase the flap dimensions and more importantly, it will allow direct closure of the donor defect[18] (Fig. 8.2).

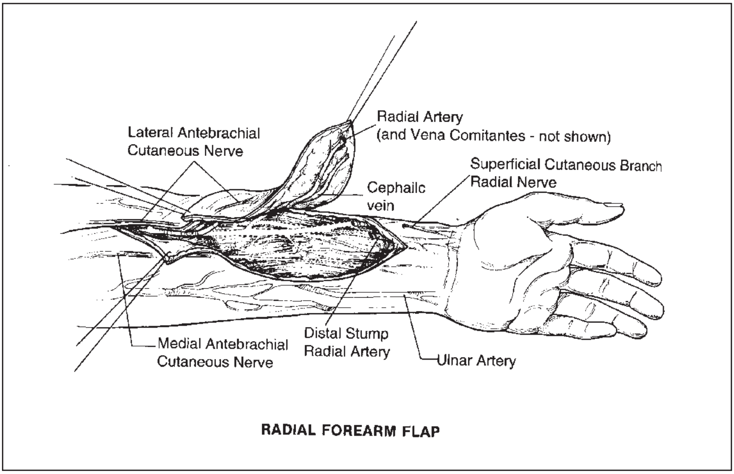

Fig. 8.2. Radial forearm flap

Harvesting Technique

The patient is positioned supine with arm on a hand table. Preoperatively evaluate the vascular supply to the hand by an Allen test and a Doppler and confirm the circulation through the ulnar artery. A line drawn from the center of the antecubital fossa to the radial border of the wrist where the radial pulse is palpable represents the course of the radial artery. Mark the flap centered over the course of the vessels. The more distal the flap design, the longer the pedicle. Make the skin incision and continue a sub-fascial dissection towards the vessels. On the distal part of the flap, identify the brachio-radialis and flexor carpi radialis tendon. The radial artery and venae comitantes will lie along the ulnar side of the bracioradialis and along the radial side of the flexor carpi radialis tendon. The cephalic vein will lie radial to the bracioradialis. Dissect under the pedicle and isolate the pedicle distally. Raise flaps from distal to proximal and isolate the vessels proximally. The dissection is done deep to the deep fascia elevating the flap from the underlying muscle. Combined flaps can include tendons and segments of the radius.

If the radius is harvested as vascularized bone, less than 40% of the cross section of the radius should be harvested, and the wrist and forearm should then be put in a cast for 3-4 weeks. Maximum attention should be focused during harvesting the flap since injury to the paritenon covering the tendons of the flexor carpii radialis, brachioradialis, and finger flexors can lead to skin graft failure and even loss of the tendons.

In most of the cases the donor site requires a skin graft for closure leaving a scar in a visible place.

Scapular Flap

The scapular flap remains probably the workhorse of skin flaps. It is a thin, usually hairless, skin flap from the posterior chest and can be de-epithliazed and used as subcutaneous fascial flap, pedicled or free flap.

The flap is perfused by the cutaneous branches of the circumflex scapular artery (CSA) and drained by its venae comitantes. The CSA is a major tributary of the subscapular artery and the CSA is the artery supplying blood to the scapula, the muscles that attach to the scapula, and the overlying skin. The length of the pedicle is 5 cm and the diameter of the artery is 2.5 mm. The vascular pattern of this territory makes it possible to raise multiple skin flaps on a single vascular pedicle or to harvest the lateral border of the scapula as an osteocutaneous flap for a complex reconstruction (Fig. 8.3).

The cutaneous territory can be 20 x 7 cm^2 and can be divided in two components: a horizontal territory (horizontal scapular flap) and a vertical territory (parascapular flap) based on the branches of the circumflex scapular artery after the vessel courses through the triangular space.

8 Innervated by the lateral posterior cutaneous branches of the intercostal nerves, this flap has no potential for being used as a sensate flap. Preliminary expansion of the territory of the scapular flap will increase the flap dimensions and permit direct donor site closure.

Flap Harvesting

Parascapular Flap

The patient is positioned midlateral or in an oblique position. The flap is elevated retrograde. Start with low medial incision. Identify the epifascial plane. The fascia is elevated cranially beneath the deep fascia, to the area of the triangular space. Complete the skin incision (the upper part). Carefully retract the flap medially. Identify the junction of the parascapular and horizontal branches of the circumflex scapula vessels. Horizontal branches are divided and the circumflex scapular pedicle is dissected into the triangular space. Identify thoracodorsal or scapular artery.

Scapular Flap

Same strategy of dissection as for the parascapular flap. The dissection is started laterally and proceeded towards the triangular space. As in the parascapular flap, the vascular pedicle can also be identified first in the course of the dissection.

Some authors favor the identification of the vascular pedicle as the first step of the dissection, especially in cases of microvascular transplant. This is accomplished with palpation of the triangular space and confirmation of pedicle location with a Doppler probe. Two approaches are available for scapular and parascapular flap elevation and preparation for the microvascular transplantation: lateral (initial pedicle identification) and medial (retrograde flap dissection). This flap can be combined with other flaps based on subscapular blood supply and may greatly facilitate certain complex reconstructions. These include the latissimus dorsi and serratus anterior flaps, which can supply additional skin, muscle, and bone (rib) if necessary.[19-21]

The primary indication for the scapular flap is a defect requiring a relatively thin, large cutaneous flap.[22] These kinds of defects are often found in the foot.[23] The

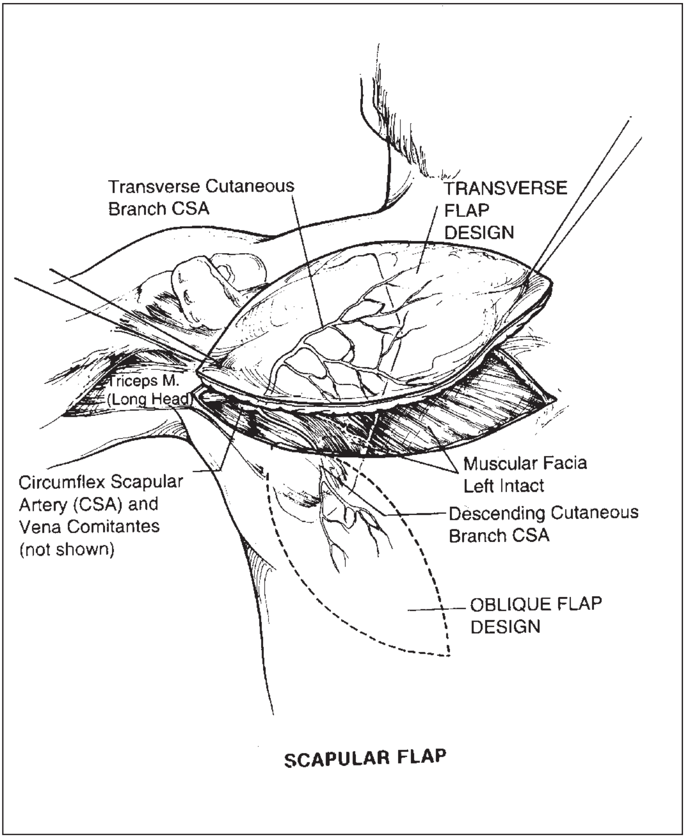

Fig. 8.3. Scapula flap

osteoseptocutaneous free scapular flap reconstruction has been described in the lower extremity.[24]

Dorsalis Pedis Flap

This is a thin sensate fasciocutaneous flap from the dorsum of the foot. It is based on the dorsalis pedis artery, which originate from anterior tibial artery and its venae comitantes.[25] The length of the pedicle is 6 to 10 cm and the diameter of the artery is 2-3 mm. The nerve supply comes form the branches of deep and superficial peroneal nerves. The size of the flap is 6 x 10 cm^2 and it can be raised as a skin flap alone or in combination with the second metatarsal bone as an osteocutaneous flap or in combination with 1st and 2nd toe transfer[26] (Fig. 8.4).

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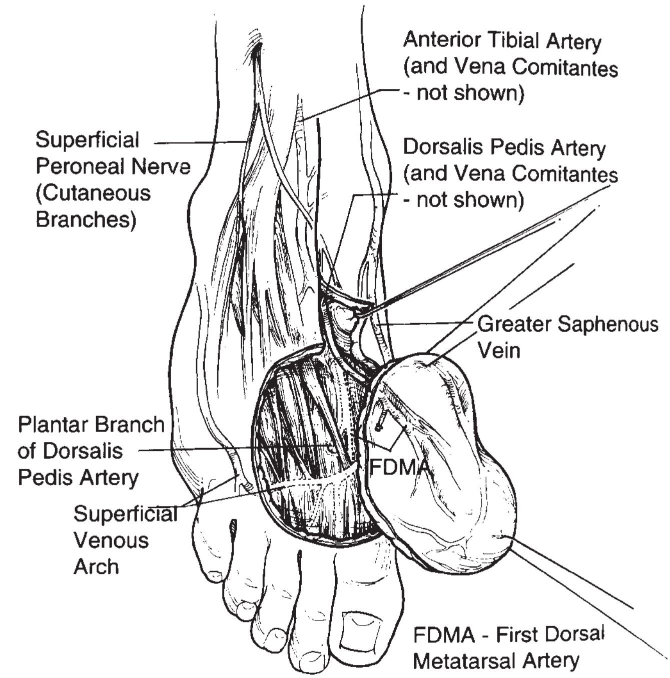

Fig. 8.4. Dorsalis pedis flap

Flap Harvesting

The patient is positioned supine with a tourniquet around the thigh. A distal incision is made for identification of the first dorsal metatarsal artery with subsequent retrograde dissection of the flap. The first dorsal metatarsal artery and branches of the deep peroneal nerve to the first web space are divided. The dissection continues from distal to proximal in a plane just deep to the deep peroneal nerve and first dorsal metatarsal artery. This plane is just above the peritenon of all the extensor tendons. The dissection is continued proximally up to the proximal head of the metatarsal. At that level the deep perforating branch of the dorsalis pedis artery is encountered. Make the medial incision of the flap and elevate the medial part of the flap with the greater saphenous vein and the dorsal venous arch included in the flap. Over the tarsal bones identify the dorsalis pedis artery. The deep branch is divided and the rest of the skin incised completely. With the upper incision completed, the extensor retinaculum is opened and the dorsalis pedis artery, its two venae comitantes and nerve are identified. The extensor hallucis brevis muscle is divided at the level of the extensor digitorum longus tendon to the second toe. Care should be taken to preserve the paritenon on the remaining tendons to provide a bed for the skin graft.

The flap can be used in the upper extremity to cover joints and tendons and in microvascular transplant of metatarsophalangeal joints in children.[27]

The donor site morbidity is of concern in this flap and it can include difficulties in primary healing with need for skin grafts, lymphedema, and hypertrophic scarring of the foot.[28]

Groin Flap

The groin flap provides a large skin and subcutaneous tissue territory based on superficial circumflex iliac (SCIA) artery and vein. The length of the pedicle is 2 cm and the diameter 1.5 mm. The dimension of the flap can be up to 10 x 25 cm^2.

Preliminary expansion of the lateral groin skin beneath the deep groin fascia will expand flap dimensions and allow direct donor site closure (Fig. 8.5).

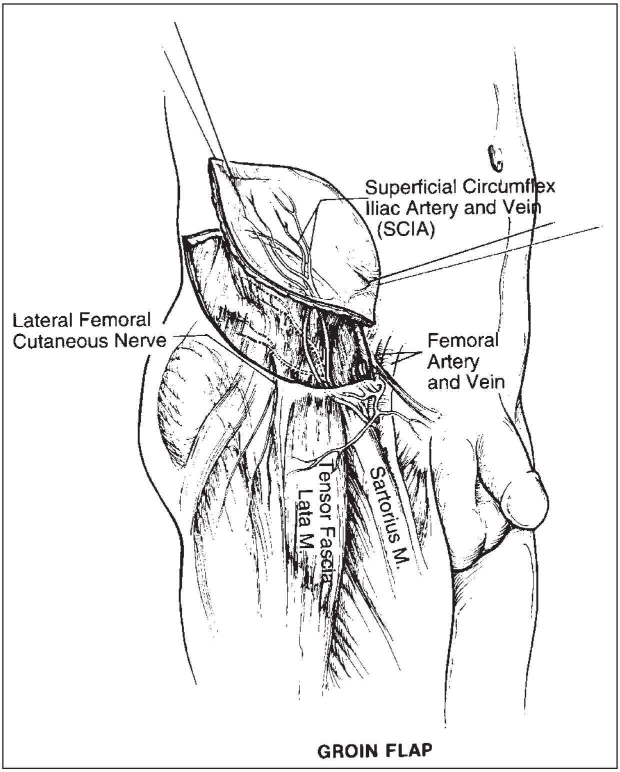

Fig. 8.5. Groin flap

Flap Harvesting

Patient position: supine position with a beanbag or folded towel placed under the posterior iliac spine on the side of the planned flap.

Medial approach is preferable for free flaps. Identify the superficial circumflex iliac artery (SCIA) prior to skin elevation. The SCIA is identified 5 cm below the inguinal line. Medial incision and identification of superficial vein anterior to Scarpa's fascia are the next steps. Identify the femoral artery and make the definition of SIEA and SCIA. Start with a lateral skin incision. The deep fascia is left intact. Next identify the lateral border of sartorius muscle. Ligate muscle branches of the SCIA branch. The lateral cutaneous nerve is divided.

Modification of the flap can be done including the sheets of external oblique aponeurosis for reconstruction of a tendon like structure to replace Achilles tendon or reconstruction of the calcaneous with an composite graft including the groin flap and iliac crest bone.[29]

The complexity of the vascular anatomy and the small diameter of the superficial circumflex iliac artery make this a less popular flap compared to other free skin flaps.[30]

Temporoparietal Fascial Flap

8

This flap can be used as a fascial or fasciocutaneous flap. The fascia covers the temporal muscle extending over the temporal fossa and lies superficial to the deep temporal fascia covering the temporalis muscle. It continues as the galea beyond the limits of the temporal fossa.

Vascular pedicle: Superficial Temporal Artery (STA) is the terminal branch of the carotid artery. The length of the artery is 4 cm and the diameter of the artery is 2 mm. The course of the vessels is on the fascia from the pre-auricular into the temporal fossa. The sensory nerve supply comes from the auriculotemporal nerve. The size of the flap is 12 x 9 cm^2 (Fig. 8.6).[31]

Flap Harvesting

Preoperatively identify the course of the vessels with a Doppler probe and mark the incision lines parallel to hair follicles.

The patient position is supine with head slightly tilted to the opposite side. Start incision by raising a pretragal skin flap. The incision extends toward the vertex of the skull over the temporal fossa. Identify and spare the superficial temporal vein anterior and remain superficial to STA. Identify STA. Dissection proceeds cephaled deep to the hair follicles. Avoid damage to the superficial temporal vein. Avoid damaging the frontal branch of the facial nerve. After cephaled completion of the dissection incise flap. Lift from deep fascial plane towards auricle. Leave flap after complete dissection for observation of perfusion.

This flap is ideally suited for covering small defects of the foot, ankle, Achilles tendon and hand. The minimal thickness of this well-vascularized flap prompts some authors to describe the technique as a "microvascular transplantation of a recipient bed".[32] This flap was found to be useful in cases of burns particularly when joint spaces or tendons are exposed after debridement.[33]

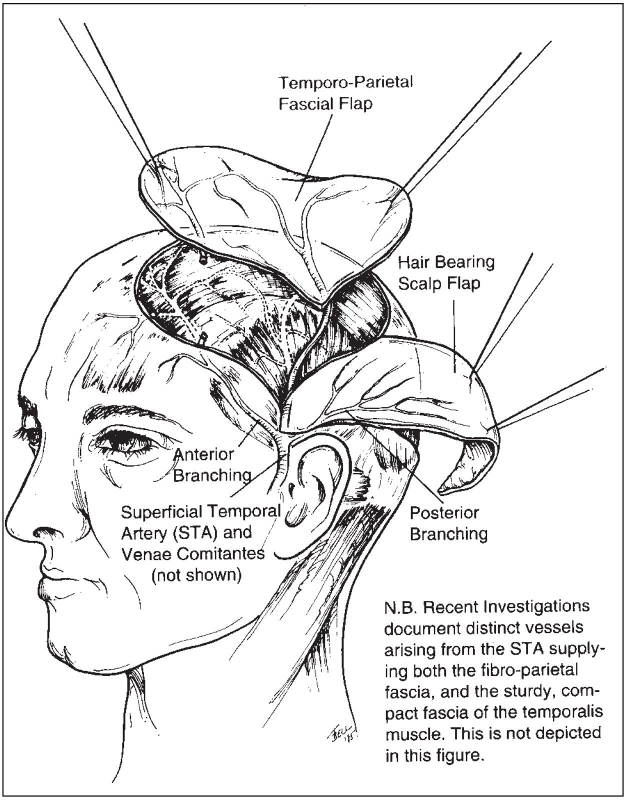

Fig. 8.6. Temporoparietal fascial flap

Muscle Flaps

The following sections on each donor muscle flap include information on

a. the muscles origin and insertion, function, vascular supply, innervation, and pedicle length;

b. the flaps (size, functional loss on removal, elevation): and

c. any special problems that may be encountered in their use.

Classification of Muscle Flap

The classification of muscle type is based on five patterns of muscle circulation.[34] A muscle for free tissue transfer must be able to survive on one vascular pedicle that is dominant and that will support the entire muscle mass. Classification is as follow:

Type 1: one vascular pedicle (extensor digitorum brevis, tensor fascia latae)

Type 2: dominant pedicle and minor pedicles (abductor hallucis longus, gracillis)

Type 3: two dominant pedicles (rectus abdominis, serratus anterior)

Type 4: segmental vascular pedicles (sartorius)

Type 5: one dominant and secondary vascular pedicles (latissimus dorsi, pectoralis major, pectoralis minor)

Unclassified potential transfer include fillet flaps and combination flaps such as the latissimus dorsi-serratus anterior muscle flap based on one dominant pedicle (thoracodorsal artery).

Latissimus Dorsi

The latissimus dorsi is a type 5 muscle (major pedicle and multiple segmental vessels).

The dominant pedicle is the thoracodorsal artery and venae comitantes, which originate from the subscapular artery and vein. Secondary pedicles are two rows (lateral and medial) of four to six perforating arterial branches and venae comitantes taking origin from the posterior intercostal and lumbar arteries and veins. The length of the major pedicle can be as long as 8 cm and the arterial diameter up to 2.5 mm. The artery enters the deep surface of the muscle in the posterior axilla, 10 cm inferior to the latissimus muscle insertion into the humerus.[35]

The motor nerve supply is the thoracodorsal nerve (C6-8) and the sensory innervation of the skin is supplied by multiple cutaneous branches of the intercostal nerves. Generally, this is not used as a sensate flap.

The latissimus dorsi is the largest transfer available, with a muscle surface area of 25 x 35 cm^2 and skin territory of 30 x 40 cm^2.[36]

The latissimus dorsi is an expandable muscle since function is preserved by the remaining synergistic shoulder girdle muscles (Fig. 8.7).

Flap Harvesting

Patient position: mid lateral, arm elevated 90°. The dissection begins with an incision along the muscle border. First identify muscle border and its relationship to the serratus muscle. Next identify the pedicle and follow the pedicle to origin in the axilla. Free anterior border of the muscle and raise the flap from a ventral in dorsal direction to the spine. Take care to coagulate or ligate the perforating vessels. Next divide the muscle distally as required. Raise muscle in the cranial direction. Next ligate the serratus branch.

For extensive wounds the latissimus can be transplanted simultaneously with the serratus muscle, on a single vascular pedicle.[37] The latissimus is commonly used in reconstruction in lower extremities for large defects.[38,39] Description of a combined flap including the ninth and tenth ribs as vascularized bone transplanted for simultaneous coverage and tibial bone reconstruction is possible but not commonly used.[40]

Serratus Anterior

The serratus anterior muscle is a thin, broad, multidigitated muscle on the lateral chest wall between the ribs and scapula.

The muscle is supplied by two pedicles, the serratus anterior branch and the lateral thoracic artery. The length of each one of the pedicles is 6-8 cm and the diameter of the artery is 2-3 mm.

The motor innervation is supplied by the C5-7 roots of long thoracic nerve and the T2-4 segmental intercostal nerve supply for sensory innervation. The vascular

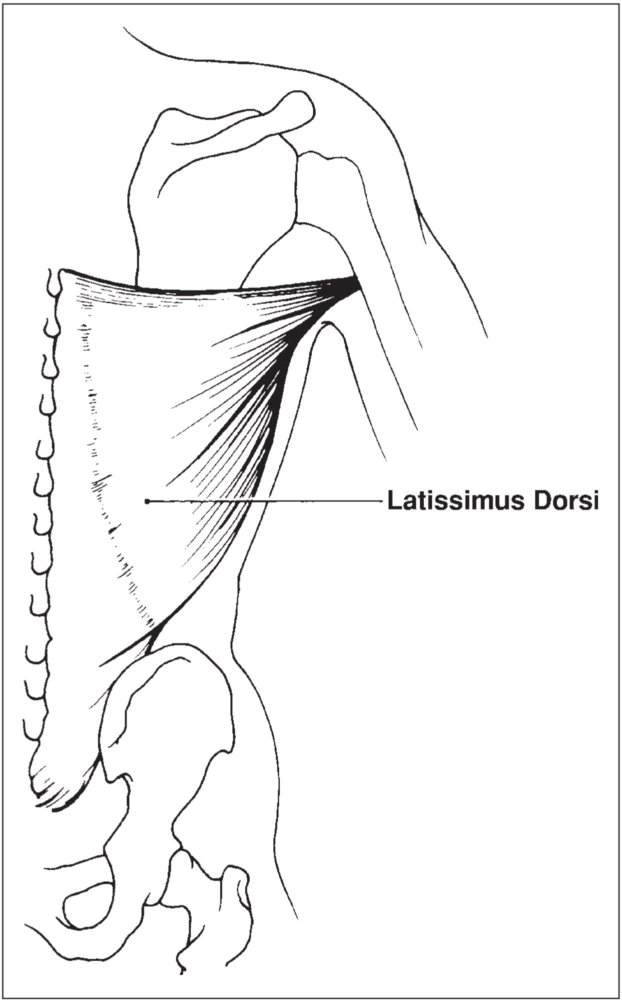

Fig. 8.7. Latissimus dorsi flap

pedicle as well as the motor nerve separates into fingers of muscles corresponding to the slips of the serratus. The size of the serratus anterior is 15 x 20 cm^2. A musculocutaneous flap of 5 x 15 cm^2 can be elevated[35] (Fig. 8.8).

Flap Harvesting

Fascia flap: The patient is placed in a lateral position, and the arm is elevated 90°. A slightly curved incision is made along the border of the latissimus muscle. Next identify the muscle border and the serratus arcade. Determine if thoracodorsal

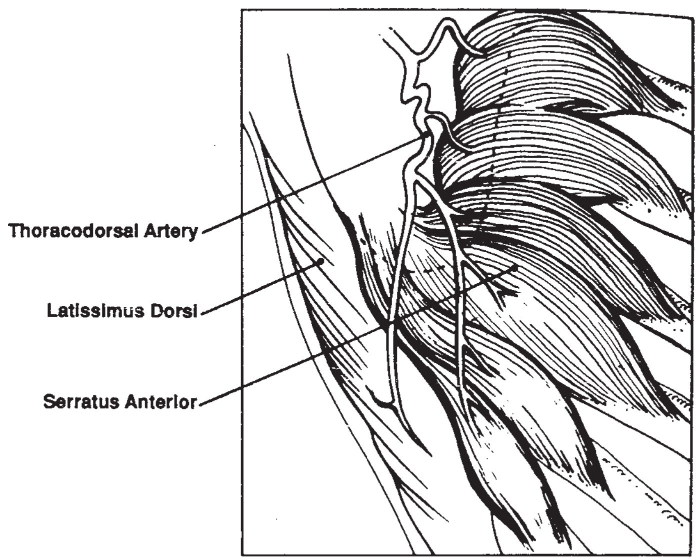

Fig. 8.8. Seratus anterior flap.

pedicle is intact and find the entrance points of the motor fibers into the muscle. Outline the flap size on the muscle surface. Release the muscle from thoracic wall. Preserve the three proximal slips to avoid winging of the scapula. The entire muscle is never taken because of the risk of winging of the scapula. Preservation of at least the upper five and preferably six slips and their intervention will decrease or totally eliminate winging of the scapula. Dissect the thoracodorsal pedicle to the length required. Transfer the flap.

Basing the serratus on its blood supply using the thoracodorsal artery makes it possible to elevate a combined latissimus dorsi and serratus anterior flap.[41] The serratus is useful as a free flap for coverage or as an innervated functional muscle.

This flap is particularly used for hand reconstruction and for foot and ankle coverage.

Rectus Abdominis

This vertically oriented muscle extends between the costal margin and the pubic region and it is enclosed by the anterior and posterior rectus sheaths. It is a type 3 muscle (two dominant pedicles) based on the superior epigastric artery and vein and inferior epigastric artery and vein. The pedicle length is 5-7 cm superiorly and 8-10 cm inferiorly.

Each of the dominant pedicles supplies just over one-half of the muscle. There is an anastomosis between these vessels that are usually sufficient to support the nondominant half if one of the two pedicles is ligated. Because of the larger size and easier dissection of the inferior epigastric vessel, this is usually used for free tissue transfer.

The motor innervation is supplied by segmental motor nerves from the seventh through twelfth intercostal nerves that enter the deep surface of the muscle at its mid to lateral aspects. The lateral cutaneous nerves from the seventh through twelfth intercostal nerves provide sensation to the skin territory of the rectus abdominis muscle. The size of the muscle is up to 25 x 6 cm. The skin territory that can be harvested is 21 x 14 cm^2 and is based on musculocutaneous perforators[11] (Fig. 8.9).

Flap Harvesting

The patient's position is supine. For a muscle flap the initial incision is located vertically over the muscle. For a musculocutaneous flap the incision extends around the skin island with an optional vertical incision extending to the muscle.

Incision of the anterior rectus sheath and dissection of the sheath from the muscle surface. Avoid muscle injury or disruption of the anterior rectus sheath at the tendinous intersection. The tendinous intersection is located at the level of the xiphoid, the umbilicus, and midway between the xiphoid and umbilicus. When a skin island is used, it is preferable to expose the muscle proximal to the skin island for accurate location of the muscle position. Then the skin island can be incised and its edges elevated to the lateral and medial borders of the rectus sheath. Separate the muscle from the posterior sheath at the distal aspect of the flap and beyond the skin island if a musculocutaneous flap is planned. Care is taken to avoid disruption of the posterior sheath below the linea semicircularis, below this line the posterior sheath consists only of transversalis fascia. After the muscle has been divided from the posterior sheath, the distal muscle is divided.

One of the complications of using this flap is the abdominal wall defect that may lead to weakness and possibly hernia formation. An advantage of this flap is the length of the pedicle and the ease of harvesting the flap with the patient in the supine position.[42]

Tensor Fascia Lata

This is a type 1 muscle (one pedicle). The origin is anterior 5-8 cm of the outer edge of the anterior superior iliac spine immediately behind the origin of the sartorius. The insertion is the iliotibial tract of the fascia lata. The dominant vascular pedicle is ascending branch of lateral circumflex femoral artery, which arises from the profunda femoris and venae comitantes. The length of the pedicle is up to 7 cm and the diameter of the artery is 2-3 mm. The motor innervation comes from superior gluteal nerve and the sensory innervation from cutaneous branches of T12. The size of the muscle is up to 5 x 15 cm^2 and the skin territory can achieve 7-9 x 22-26 cm^2.[43]

Flap Harvesting

The patient is positioned supine and the entire lower extremity is prepped so that the hip can be adducted, abducted and rotated during elevation. The initial incision for elevation of the flap may be made along the anterior, posterior or distal border of the flap. After the distal incision, identify the fascia lata below the skin. The TFL muscle can be identified after the dissection advances more proximally. Extend the anterior and posterior incision from below upward toward the anterior superior iliac spine and the border of the iliac crest. Identify the terminal branches of the lateral circumflex femoral artery 10 cm below the anterior superior iliac spine and continue to dissect deep to the rectus femoris to develop a long vascular pedicle.

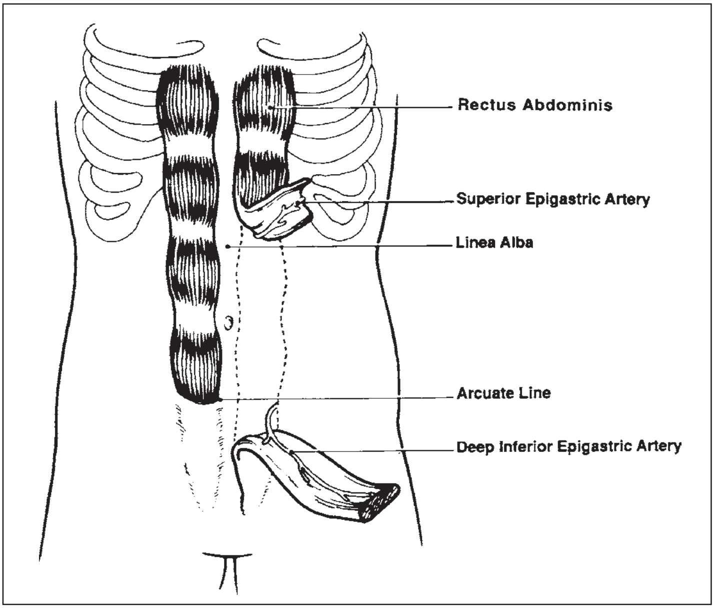

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Fig. 8.9. Rectus abdominis flap.

Continue the dissection above the pedicles to separate the TFL from the underlying gluteal muscle. The upper incision is then completed, the muscle transected, and the flap prepared for microvascular transplantation.

Communications between the origin of the muscle and the outer lip of the anterior iliac crest allow transplantation of the muscle with vascularized bone. The flap can be transferred as a functional unit and can be useful for foot and lower leg coverage.[44]

Gracilis

The gracilis muscle is a type 2 muscle (dominant pedicle and several minor pedicles.) It is a thin, flat muscle that lies between the adductor longus and sartorius muscle anteriorly and the semimebranosus posteriorly. The dominant pedicle is the ascending branch of medial circumflex femoral artery and venae comitantes. The length of the pedicle is 6 cm and the diameter of the artery is 1.6 mm. The minor pedicles are one or two branches of the superficial femoral artery and venae comitantes. Their length is 2 cm and the diameter is 0.5 mm.[45]

Motor innervation is provided by the anterior branch of the obturator nerve which is located between the abductor longus and magnus muscles, and usually enters the muscle above the level of the dominant vascular pedicle The anterior femoral cutaneous nerve (L2-3) provides sensory innervation to the majority of the anterior medial thigh.

Function: This muscle functions as a thigh adductor. The presence of the abductor longus and magnus makes it an expendable muscle.

Flap: The size of the muscle is 6 x 24 cm^2. The skin territory is 16 x 18 cm^2, but the skin over the distal half of the muscle is not reliable when the flap is elevated based on its dominant vascular pedicle with division of the minor vascular pedicles. In obese patients the musculocutaneous flap may be too bulky, necessitating use of a skin graft placed on the muscle.

Flap Harvesting

Patient position: Supine hip and knee flexed, leg abducted. A line is drawn between the pubic tubercle and medial condyle of the femur. Since the muscle is made 2-3 cm posterior to the line, a parallel incision is made 2-3 cm posterior to this line. Identify and preserve the greater saphenous vein (anterior to the incision). Incise the fascia and identify the gracilis muscle medially and posterior to the adductor longus muscle. Divide the muscle distally. Ligate minor pedicles. Proceed with dissection cephalad. Retract adductor longus proximally. Expose the pedicle 6-12 cm distal to pubic tubercle. Protect medial cutaneous nerve on surface of adductor magnus. Clip or ligate small branches. Divide muscle superiorly (Fig. 8.10).

If skin in island is included in the flap it will be located over middle or proximal portion. The incision is done down to the fascia and the fascia lata will be included in the dissection. The rest of the dissection is similar to the dissection of the muscle alone.

Omentum

The omentum is a visceral structure containing fat and blood vessels within a thin membrane. It extends from the stomach to the transverse colon and beyond covering the anterior peritoneal contents.

It has two dominant pedicles: right gastroepiploic artery and vein with a length of 6 cm and a diameter of the artery of 2-3 mm, and a left gastroepiploic artery and vein with a pedicle length of 4 cm and diameter of the artery of 2 mm. It may be as large as 40 x 60 cm^2 (Fig. 8.11). Prior intra-abdominal surgery may preclude use of the omental flap because of extensive omental inflammatory adhesions.

Its pliability and rich lymphatic network make it ideal to fill cavities and fight infection. The omentum is particularly ideal for obliteration of irregular dead space cavities and thus has been effectively utilized in providing coverage after saucerization for chronic osteomyelitis.[46]

Flap Harvesting

The incision is at the abdominal midline. Release the areolar attachments of the omentum from the transverse colon so the omentum remains hanging on the greater curvature of the stomach. Return the omentum to the inferior abdominal cavity and expose the anterior paired layer attachments to the greater curvature of the stomach. Next divide the short vascular branches between the gastroepiploic arch and the greater curvature of the stomach. At that point a decision is made whether to base the flap on the right or left gastroepiploic artery and vein. If the omentum will be based on the right gastroepiploic artery and vein then the left gastroepiploic

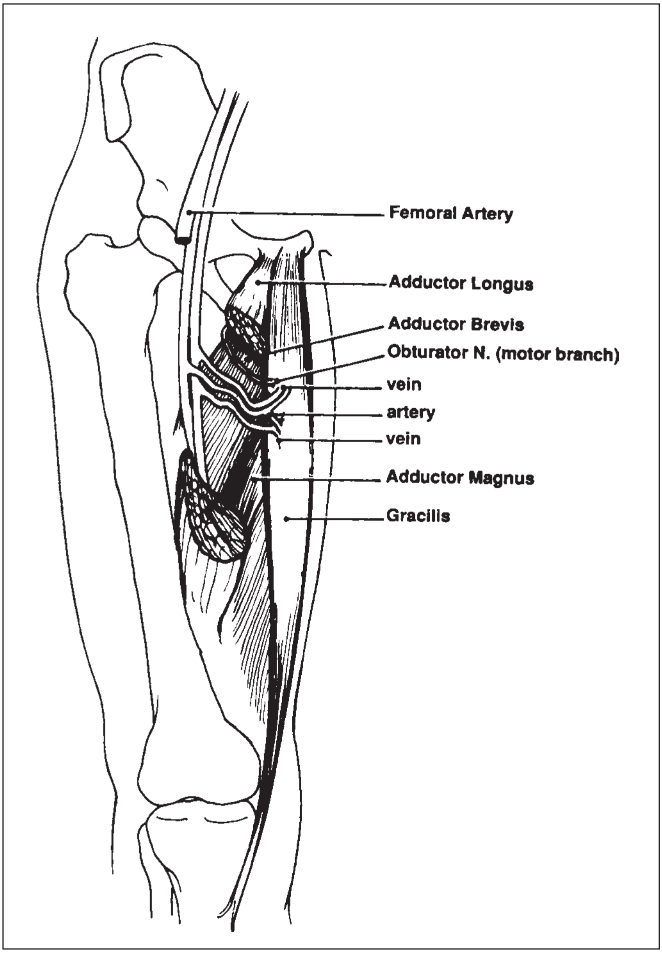

Fig. 8.10. Gracillis flap.

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artery and vein are ligated immediately distal to their junction with the splenic artery and vein. The omentum is mobilized within 3 cm of the gastric pylorus.

If the omentum will be based on the left gastroepiploic artery and vein, then the right gastroepiploic vessels will be divided and ligated along the greater curvature of the stomach immediately proximal to the pylorus. The greater omentum is mobilized from the greater curvature of the stomach to a point 5-7 cm proximal to the gastrosplenic ligament where standard flap elevation is completed.

A nasogastric tube is inserted for 24-48 hours after the operation to decompress the stomach. This prevents gastric distention that among other things might dislodge any of the vascular ligations along the greater curvature.

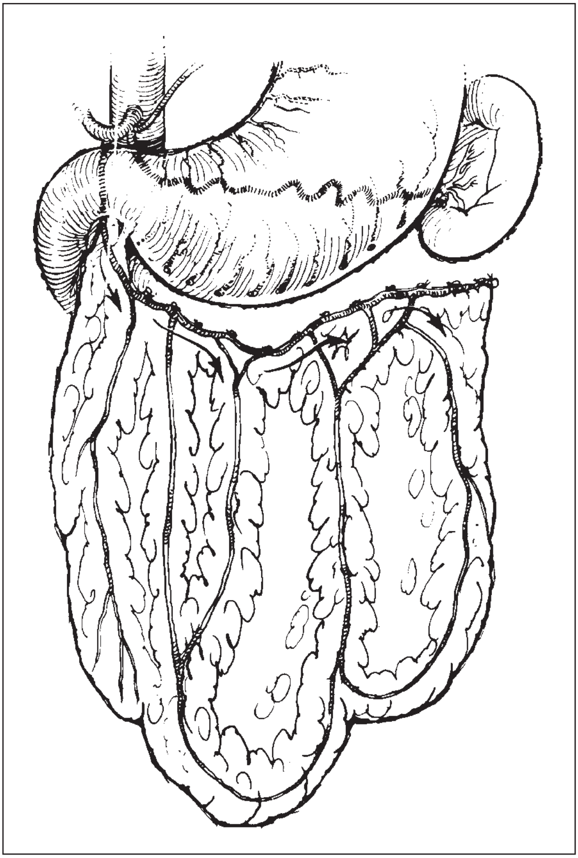

Fig. 8.11. Omentum flap.

Postoperative Care

Postoperative care of free tissue transfer patients requires that patients be adequately hydrated. Maintenance of proper body temperature and hematocrit is also important Routine heparinization and anticoagulation is not utilized.

Flaps are usually monitored for a minimum of 5 days with a laser Doppler in addition to clinical observation. While the immediate postoperative period of 24-48 hours is critical, there have been late occasional failures; thus, laser Doppler monitoring should be continued for 4 or 5 days.

Extremities should be elevated at all times to augment venous return. Lower extremity patients are not allowed to ambulate postoperatively for a minimum of three weeks. The inosculation and the healing of the flap to the wound bed, the selection of muscle or skin, and the “take” of the skin graft, are factors that go into the timing to determine dependency of the lower extremity. Those patients that have reconstruction around the foot and ankle are most prone to increased venous pressure and resultant edema of the flaps. This edema can result in the dehiscence of the free flap from the surrounding tissue bed. For this reason, extremity patients are required to keep their limbs elevated and undergo bed to chair transfer for a minimum of three weeks. Some experimental data suggests that this timing can be shortened. However, it is the author's experience that this is the amount of time it takes for the flap to mature and develop a sufficient venous return to withstand hydrostatic pressure associated with standing.

Prior to proceeding with any other reconstruction such as bone grafting (such as in a case of open tibia fracture), or tendon transfers, all wound surfaces must be epithelialized. There must be no edema, cellulitis, granulation tissue, or sinus tracts that could compromise the next stage of reconstruction. For example, in cases of a free muscle flap in the distal third of an open tibia fracture that ultimately requires bone grafting, it is essential that all skin grafts be totally epithelialized to decrease skin colonization of bacteria. It is the author's preference to remove the external fixator, clean the pin sites, and place patients in a cast until the pin tracts heal. The flap can be then elevated and an autogenous bone graft can then safely be performed.

Monitoring

Monitoring of free tissue transfer is essential to assure transplant success. Many different monitoring devices and techniques have been used with varying levels of success. As is true in many situations in medicine, the availability of many solutions to a problem suggest that none is superior or ideal.

An ideal flap monitoring should satisfy several criteria. It should be harmless to the patient or the flap, objective, reproachable, applicable to all types of flaps and inexpensive. It is important that any monitor be capable of prolonged monitoring and respond rapidly too circulatory changes. Postoperative monitoring techniques can be grouped in four categories:

1. clinical evaluation,
2. direct vessel monitoring,
3. indicators of tissue circulation and
4. metabolic parameters related to perfusion.[47]

Clinical evaluation remains the gold standard by which all methods of monitoring need to be compared. This involves observation of skin color, temperature, capillary refill and bleeding characteristics. Clinical observation fulfills many of the criteria of the ideal monitoring system. It is cheap, readily available, and can provide a dynamic picture. The disadvantages are the need for experienced personnel, its use being confined to monitoring surface skin flaps and muscle flaps. Changes are often initially subtle, and by the time they are clinically apparent, salvage of the flap may be impossible because of irreversible tissue damage.

Direct vessel monitoring can be done by electromagnetic flowmeters. Readings are based on measuring the electric potential induced by blood flow. The ultrasonic Doppler measures sound waves reflected from columns of moving blood cells. Thermocouples measure the temperature difference between pre-and postanastomotic sites on the vascular pedicle using two microthermocouples.

This category of monitoring includes photopletismography, pulse oximetry and laser Doppler flowmetry which based on the same general principles as ultrasound

Doppler, but measures the frequency shift of light, rather than sounds wave reflected from moving red blood cells.

Transcutaneous oxygen monitoring and invasive measurements of PO2 check the perfusion of tissue transplantations based on metabolic parameters. Levels of tissue oxygen tension have been monitored in flaps and have been shown to reflect the quality of capillary circulation.[48]

Monitoring is usually performed in the intensive care unit setting or a step-down setting, depending on the condition of the patient. Absolute values of laser Doppler measurements, patterns, and trends of flow can give valuable information about the dynamic perfusion range of blood flow over time. Low absolute values of perfusion, as well as relative change to the initial flow, are alarming signs and immediate clinical evaluation of the flap should be performed. It is the author's preference to use the laser Doppler for monitoring of free flaps. The standard practice in our center is to routinely monitor patients in intensive care unit for the first 24 hours because this is when the problems most frequently occur following free tissue transfer.

A relative flow falls to 50% of the initial flow of that flap that remains low for 30 minutes or more, indicates an aggressive observation of the flap.

In cases of absolute flow lower than 0.4 LDF units for 30 minutes, exploration should be strongly considered. This flow value is typically inconsistent with viability of the flap regardless of flap type, recipient site, or blood flow history.

In cases of abnormal laser Doppler values, artifact should be ruled out. Falsely low readings can occasionally be the result of a probe becoming slightly detached from the flap. In addition, low readings can be caused by hypovolemia, anemia, and hypothermia.[49] Therefore, it is important to closely examine not only the laser Doppler equipment, but also the general condition of the patient. Falsely elevated measurements can be caused by vibration, motion of the probe or tissue, location of the probe over a large vessel, or extreme variation in the hematocrit. Success of free tissue transfer should be on the order of 95-99%.

Flap Failure and Management (Acute)

Acute complications occur usually in the first 48 hours and includes venous thrombosis, arterial thrombosis, hematoma, and hemorrhage and excessive flap edema. Arterial insufficiency can be recognized by decreased capillary refill, pallor, reduced temperature, and the absence of bleeding after pinprick. This complication can be caused by arterial spasm, vessel plaque, torsion of the pedicle, pressure on the flap, technical error with injury to the pedicle, a flap harvested that is too large for its blood supply or small vessel disease (due to smoking or diabetes). Management of arterial compromise requires prompt surgical intervention to restore the blood flow.[50] Pharmacological intervention includes vasodilators, calcium blockers and anticoagulants for flap salvage presenting with arterial insufficiency.[51]

Venous outflow obstruction can be suspected when the flap has a violaceous color, brisk capillary refill, normal or elevated temperature and production of dark blood after pinprick. Venous insufficiency can occur due to torsion of the pedicle, flap edema, hematoma or tight closure of the tissue over the pedicle. The venous outflow obstruction can result in extravasation of the of red blood cells, endothelial break down, microvascular collapse, thrombosis in the microcirculation and finally flap death. Given the irreversible nature of the microcirculatory changes in venous congestion that occurs even after short periods of time, the surgeon must recognize venous compromise as early as possible.

These complications can occur alone or in any combination. The clinical observation and the monitoring of the patient (such as with laser doppler) should alert the surgeon, who has to decide between conservative and operative intervention. Conservative treatment may include drainage of the hematoma by the bedside, or release of a few sutures in order to decrease pressure. In cases of venous congestion leeches may be helpful if insufficient venous outflow cannot be established despite a patent venous anastomosis. The leeches inject a salivary component (Hirudin) that inhibits both platelet aggregation and the coagulation cascade. The flap is decongested initially as the leech extracts blood and is further decongested as the bite wound oozes after the leech detaches.[50]

The donor site should be given the same attention as the recipient site during postoperative period. Complications of the donor site include hematoma, seroma, sensory nerve dysfunction and scar formation.

Treatment of Failure (Late)

Occasionally free flaps, despite early return to the operating room for vascular compromise, do fail. Options for management include the performance of a second free tissue transfer, noting the technical or physiologic details that led to initial failure. Most of the time, free tissue transfers that fail are due to technical errors in judgement; whether they be flap harvest, compromise of the pedicle during the harvest, improper micro-vascular technique during anastomosis, improper insetting resulting in increased tissue tension and edema or postoperative motion of the extremity resulting in pedicle avulsion. While this is rare, it does occur. The next decision made by the operating surgeon as to the management of this patient is based on several factors. Obviously if a patient requires a free flap in the first place, a second free flap should be considered. If a decision is made not to redo the flap, it could be left in place using the so-called Crane principle in hope that underlying granulation will be sufficient such that skin grafting can be performed once the necrotic flap is removed.

The Crane principle can be applied to cases where a local flap or free tissue transfer that goes on to necrosis in part or totally performs a biologic dressing or eschar over a wound bed. If there is no infection then the eschar can be left on the would bed with hopes that some healing can occur underneath the eschar. This wound be in the form of granulation tissue that may form under the eschar. Ultimately, the eschar could be removed and with an appropriate granulation bed, the wound can be skin grafted obviating the need for another free tissue transfer. By observing the wound, if such a bed is not produced then a second flap must be considered.[52]

It is the author's preference that this not usually is done in that the flap can become a source of sepsis and further compromise local tissues. Necrotic nonviable flaps should be removed and a temporary wound dressing such as a bead pouch or wound hemo-vac is utilized. Occasionally when flaps fail in severely compromised extremities, consideration can be given to amputation in that the morbidity of a second free tissue transfer and perhaps the resultant extremity state renders the extremity less favorable for salvage and more favorable for amputation. If a second free flap is considered, obvious errors that lead to flap compromise need to be recognized. It may be prudent to obtain an arteriogram, evaluate coagulation profile, and research other issues that lead to failure.

Endoscopic Harvesting

Following the introduction of endoscopic techniques in almost every field of surgery, the application of the techniques in reconstructive microsurgery represents the natural evolution of this trend. Less postoperative pain, smaller scars in the donor area better visualization of the operative field with the magnified video and better hemostasis are only a few of the advantages of this technique. These advantages have been seen in a recent series of patients in which latissimus dorsi harvesting was compared between the endoscopic technique and the traditional technique.[53] Successful microvascular transplantation of gracilis muscle harvested with endoscopic guidance are also described in the literature.[54],[55]

Prefabrication of Flaps

Prefabrication of flaps allows custom flaps to be constructed based on what is required for a specific defect. The exploration of this new frontier may increase the possibility of reconstructive capabilities and decrease the donor morbidity of classical reconstructions. Depending upon the specific application of the prefabrication, one or more of the following advantages may be offered: 8

1. Specific preferred blocks of tissue, that are not naturally perfused by anatomically well defined axial vessels, or by a reliable pedicle that is easy to use for transfer may be used. One examples is skin flaps that need to be very thin (the axial pedicles of all known flaps enter from the deep side, and a significant amount of subcutaneous tissue must necessarily be incorporated).
2. A larger flap of specialized tissue may be transferred than is naturally perfused by the pedicle. Examples include pretransfer delay of a cutaneous flap to include a larger skin island and pretransfer expansion of a flap to generate an additional amount of precious specialized tissue. By extending the limits of perfusion delay allows the transfer of a much larger amount of tissue than would be allowed by the original pedicle.
3. The morbidity of a donor site can be reduced. Examples include pretransfer expansion of a flap to allow primary closure of the donor site and transfer of the lower abdominal skin based on an induced pedicle that spares the rectus muscles and the integrity of the abdominal wall.
4. The satisfactory functional status of the replacement part may be ascertained prior to transfer. Thus, that which had been a lengthy multiple-stage posttransfer reconstruction can be converted into an elegant, single step transfer of a finished functional part or organ.

Current clinical methods of flap prefabrication can be considered to be based on one or more of the following fundamental principles of reconstructive surgery:

1. delay or expansion

2. grafting; pretransfer grafting of flaps is necessary when complete graft take is mandatory to the success of the reconstruction, and when posttransfer grafting is neither feasible nor practical.
3. vascular induction using staged flap transfer. This method is based upon the well-established principle of staged flap transfer, for which the "vascular carrier" is the contemporary microvascular refinement of the old wrist carrier. The concept is that a small flap of muscle, fascia, intestine, omentum, or even an arteriovenous bundle or fistula can become a "vascular carrier" and can be induced to provide an alternative blood supply through neovascularization to a larger block of tissue after a relatively short staging period.[56]

A fourth method of flap prefabrication makes use of recent advances in cell biology to induce the transformation of a flap from one tissue type to another. An application of these advancements can be found in bone and joint reconstruction, which is still most commonly performed with less than ideal alloplastic materials and remains a formidable challenge despite advances in free tissue transfer. With the possibility of inducting mesenchymal tissue to differentiate into bone, a simple muscle flap may be molded and transformed into a vascularized bone graft of desired shape and size.[57,58]

The search continues for new methods, which will result in faster and easier methods for microvascular anastomosis. Representing this group of instruments, staplers may have a more important role in microsurgery in the future. They shorten the operating time and have proven to be safe.[59] The vessels suitable for this technique should be chosen carefully and the surgeons using this technique should be also experienced in conventional microsurgery.

It is expected that the time-consuming procedure of microvascular surgery using interrupted sutures will be replaced more and more by the use of running sutures. Furthermore, refinements in laser welding and the development of new glues may take over the role of sutures. The operating microscope itself may also vanish in time. Many microsurgeons prefer to use high-magnification loupes, in which they are able to achieve good results.[60,61] Furthermore advances in video technology now enable the surgeon to view a microsurgical field on a monitor in three dimensions without the necessity to look through the microscope eyepieces.[62]

Microsurgery Cost and Outcome Evaluated Thoroughly

The time-consuming and costly nature of this microsurgery requires those appropriate indications and patient management is delineated; to operate in this cost-conscious time, financial as well as functional outcome determinations are critical. Some groups, however have assembled cost estimates and made initial inroads into outcomes and measurements of cost effectiveness.[63,64]

The versatility and vascularity of free tissue transfers have made them indispensable tools for reconstructive surgeons in orthopedic surgery. Although free flaps procedures can provide definitive treatment in a single operation, they are expensive and require specialized practitioners. The cost of microsurgery in treating the spectrum of eligible patients has not been defined.

Clearly a reduction in complication rates would reduce the cost of these procedures. Currently, efforts are under way to reduce free flap costs at all stages of care by shortening the operating time with the use of new devices, shortening the monitoring time postoperatively and even exploring in selected patients the possibility of using an outpatient monitoring system.[65] In this area of managed care and capitation, expensive procedures are often targeted in cost-containment efforts. Free flap procedures are costly but they are also effective.[66]

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Thumb and Finger Reconstruction with Microsurgical Techniques

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Introduction

Congenital absence or loss of a digit from trauma or disease can lead to severe functional problems in a hand. Over the years, many techniques have been developed for digital reconstruction. Nowadays, microsurgical free tissue transfers, usually using toes as donor material, have become routine operations, and are commonly offered to patients as the best method for functional restoration.

After a brief historical introduction, this Chapter reviews the basic principles for reconstructing function in damaged hands. Indications for toe to hand transfer are discussed. This is followed by a description of the anatomy and surgical technique for toe transfers. Postoperative management is presented. Results and complications are then reviewed.

Historical Background

The first toe transfer was described by Nicoladoni who, in 1897, successfully completed a pedicled toe transfer to reconstruct the thumb in a two stage procedure in a five-year-old boy. More recently transfers have been done microsurgically. Initially Buncke demonstrated that free toe transfers could be achieved in the Rhesus monkey. Not long after, in 1969, Cobbett did the first free toe transfer in a human patient. Since then, there have been many surgical toe transfers. As experience with this form of reconstruction has increased, multiple variants have developed. These include big toe transfers, second toe transfers, second and third toe combinations, and a number of different partial toe constructs. Microsurgical procedures have now become one of the standard options for digital reconstruction.[1,2]

Basic Principles of Digital Reconstruction

General Considerations

Digital reconstruction needs to be carefully planned. It is vitally important to insure that, when finished, the hand is functionally and aesthetically improved.

In children with congenital anomalies of the hand, a prediction of future function is the main factor that determines the need for surgical reconstruction, and the technique that should be used.[3]

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In adults with deficits resulting from mutilating injuries of the hand, assessment should include consideration of the patient's own goals for work and lifestyle-related activities, a level of cosmesis that is acceptable, and the motivation to potentially undergo multiple operations and extended hand therapy. Sometimes it might be beneficial to evaluate the nature of the patient's disability in the workplace itself, and to try to gauge his/her capacity for adaptation.

There are no therapeutic algorithms or rigid guidelines for determining the correct or best management options. Each situation has multiple variables related to the patient's anatomical deficiencies, psychological state, and functional needs. There are, however, important basic principles, which should be adhered to as closely as possible.

Planning at the Time of Acute Injury

When treating severe hand injuries, it is important to make good management decisions on the day of injury. In the emergency situation it is very difficult to get to know the patient well enough to accurately predict future needs. The surgeon should, however, at least find out the patient's occupation, hobbies, outside interests, and hand dominance. Some patients may have psychosocial problems with amputations in the hand, for cultural reasons.

At the initial operation wounds should be excised sparingly and in a manner that will preserve maximal function. In particular, surgeons should not forget that injuries resulting in a "metacarpal hand" result in great functional loss.[4] The 'metacarpal hand' has almost no prehensile ability. The minimum length of digits to allow grasp is through the interphalangeal joint for the thumb, and through the middle of the proximal phalanx for fingers. It is useful to try to envision the final reconstructed hand on the day of injury. The initial operation should set the hand up (and not cause difficulties) for future reconstructive stages. Decisions taken on the day of injury may have a profound effect on the final outcome.

Digital Reconstruction

A number of factors need to be considered when digital reconstruction is planned: length, position, mobility, power, stability, sensation, and cosmesis. For the reconstruction to be functionally and aesthetically satisfactory, the surgeon should restore as many of these factors as possible.

In addition to considering factors important for reconstructing individual digits, it is vital to insure that the reconstruction improves hand function as a whole. Digital reconstruction must be aimed at improving one or more of the various forms of pinch (tip pinch, pulp pinch, key pinch, chuck pinch) and / or grip (cylindrical grip, spherical grip, power grip, hook grip) in addition to providing better flat hand function, and cosmesis. It should be remembered that length, stability, and sensibility are most important in the radial digits, which are responsible for dexterity functions, whereas mobility is more important in the ulnar fingers, which provide power grip functions.

It is not necessary to have five digits on a hand for good function. On many occasions it may be better to have less digits, especially if those present are able to provide good function, are not painful, and have good sensibility. If a reconstructed hand is to have less than five digits, care should be taken to avoid creating functional problems, such as a gap between fingers in the central part of the hand, or a tight first web space.

Thumb Reconstruction

Functionally, the thumb is the most important digit. It is different from the fingers and needs special consideration. Anatomically it has one less phalanx, is broader, and is in a different plane, separated from the fingers by a wide first web.

When reconstructing a thumb, it is necessary to:

1. restore adequate length for opposition
2. abduct the thumb so that it can oppose the other digits
3. provide the adduction and flexion necessary for strong pinch and grip
4. provide stability, necessary for effective pinch and grip
5. restore as much mobility (especially of the basal joint) as possible
6. restore as much sensation is possible
7. it is also desirable to insure that it is aesthetically pleasing.

Donor Site Considerations

The most important basic principle relating to donor sites is that morbidity should be minimal. Scars should be as small as possible. Function should not be compromised. Donor site issues should be discussed with patients preoperatively, as part of surgical planning. If donor tissue is to be taken from a foot, activities important to the patient, such as the desire to wear certain kinds of footwear or to take part in specific athletic activities, need to be carefully evaluated.

Nonmicrosurgical Techniques for Digital Reconstruction

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A wide variety of operations have been described for thumb and finger reconstruction. Sometimes one of the older techniques (Table 9.1) may be preferable to a complex microsurgical procedure. The majority of these techniques were developed for thumb reconstruction because it is the most important digit. All options should be considered in the planning stage.

Web Spaced Deepening

This gives a small amount of functional improvement by slightly increasing the length of and implications stump. It has been used for amputations in the region of the interphalangeal joint of thumb or proximal interphalangeal joint of fingers.

Nonvascularized Phalangeal Transfers

Nonvascularised toe phalanx transplants can be used to add length to digits in children. Continued growth has been reported in the transplanted phalanges, provided the child is very young, and the periosteum is left intact at the time of operation. The main indication is constriction band syndrome.

Distraction Lengthening

Metacarpal lengthening can be used for improving functional in thumb amputations. Up to 2 cm of length can be produced by this method. The disadvantage is that the web is also pushed more distally and may need to be deepened as an additional surgical stage. Phalangeal distraction lengthening can also be used to produce up to 2 cm of lengthening in thumb or fingers.

Table 9.1. Techniques for digital reconstruction, which do not involve microvascular surgery

Web space deepening
Nonvascularised phalangeal transfers
Distraction lengthening
Metacarpal lengthening
Phalangeal lengthening
Gilles 'cocked hat' procedure
Osteoplastic reconstruction
On top plasty
Pollicisation

Gilles Cocked Hat Procedure

Now mostly of historic significance, this procedure has been used for amputations in the region of the metacarpophalangeal joint of the thumb. A first web based skin flap is elevated and used to cover a bone graft lengthening of the thumb ray. Its main disadvantage was that the bone graft tended to atrophy.

Osteoplastic Reconstruction

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This technique for thumb reconstruction uses a combination of skeletal lengthening with bone graft and distant flap (groin) for soft tissue cover. A neurovascular island flap from the long (median innervated) or ring (ulnar innervated) fingers can also be incorporated to provide sensibility. The main disadvantage is that, in adults, the cerebral cortex is not able to adjust, and sensation continues to be interpreted as coming from the island flap donor site.

On Top Plasty

A useful procedure when there is a thumb amputation through, or just proximal to, the metacarpophalangeal joint, associated with an amputation of the index finger through the proximal phalanx. The index stump is pollicised, taking the distal end of the second metacarpal, the metacarpophalangeal joint, and proximal phalanx to the thumb. This procedure adds a joint to the thumb, in addition to providing increased length.

Pollicisation

Pollicisation of the index is still commonly used for the management of absent thumbs in children with radial dysplasia. In adults it may be used for amputations in the region of the first carpometacarpal joint, but has the disadvantages of producing a very spindly looking thumb and reducing overall grip strength in the hand.

Microsurgical Digital Reconstruction–Indications and Technical Options

Since the introduction of microsurgical toe-to-hand transfers, much has been learned about the indications for the procedure. In addition, many technical variations and modifications have been described (Table 9.2) to solve problems and to address specific clinical needs.

Table 9.2. Described techniques for microvascular digital reconstruction

- Great toe transfer
- Second toe transfer
- Second toe transfer with dorsalis pedis flap
- Partial toe transfers
  - Trimmed toe transfer
  - Wrap around flap
  - Extended wrap around flap
  - Toe pulp transfer
- Vascularized nail graft
  - Great toe partial nail preserving technique
  - Combined transfers
    - Combined second and third toe transfer
    - Wrap around flap plus second toe proximal phalanx
    - Twisted toe flap
    - Pollicised index finger stump plus lateral arm flap
    - Pedicled groin flap plus toe transfer
    - Osteocutaneous lateral arm flap
    - Transfers including epiphyseal plates
  - Unusual cross hand finger transfers
    - Cross hand ring finger transfer
    - Transfer of damaged or abnormal digits
  - Polydactylous toe transfer

Congenital Anomalies

It is also important to remember that children are remarkably adaptable to seemingly severe deformities. Microsurgical toe-to-hand transfers, however, have the potential for producing significant functional improvement in a number of different types of congenital anomaly.

The congenital anomalies for which toe transfer is considered include adactaly (aplasia, preaxial dysplasia) thumb hypoplasia, and constriction band syndromes. The goals of reconstruction are to provide prehensile grip, pinch, and bimanual grasp. The reconstructed hand will never function normally, but it is usually possible to make it into a good helping hand.

In adactaly and related conditions, a toe-to-thumb transfer is usually the most important procedure. In symbrachydactly, finger reconstruction with lesser toe transfers may be useful.

In children with a hypoplastic thumb, toe-to-thumb transfer is indicated if pollicization is not an option. The size and structure of the hypoplastic thumb, and the presence of an intact carpometacarpal joint are critical considerations when the possibility of toe-to-thumb transfer is being evaluated.

There is debate about the best age to perform microsurgical reconstruction in children with congenital hand anomalies. It is important to consider the psychological effects on both the child and the parents (see also Chapter 11).

Reconstruction after Mutilating Injuries of the Hand

Options for Thumb Reconstruction

Great toe-to-hand transfer is indicated for thumb amputations at, or close to, the level of the metacarpophalangeal joint. Great toe transfer provides a broad area for oppositional contact, but can be too bulky. Great toe transfers cannot include a metatarsal, since the first metatarsal head must remain in the foot if severe gait disturbance is to be avoided. If metacarpal reconstruction is needed, a second toe donor site should be considered. Patients may prefer the cosmetic appearance of a second toe donor site to the defect left by great toe harvest.

Second toe transfer to the thumb can also be cosmetically unappealing. It can have a claw appearance. A second toe-to-thumb transfer results in a three phalangeal thumb. Interphalangeal joint stability can be difficult, and secondary interphalangeal fusions may be necessary to resolve this problem. There is minimal cosmetic deformity in the foot after the second toe has been harvested, especially if the web space between the first and third toes is closely approximated. Foot function has not been shown to change significantly with either choice of donor toe.

The trimmed great toe transfer is a debulked version of the great toe transfer tissue. Nail, soft tissue and bone are removed from the medial aspect. This technique is aesthetically more pleasing than a great toe transfer, but it is technically more challenging, and the transplant loses about 10 degrees of interphalangeal joint motion.

Other variations of the basic toe transfer procedures have also been described. These modifications enable specific functional and/or anatomical reconstructions to be done in a customized manner. They have been designed to be aesthetically appealing and to reduce donor site morbidity. Commonly used variations include second toe transfer with dorsalis pedis flap, wrap around flap, extended wrap around flap, toe pulp transfers, vascularized nail grafts, and the great toe partial nail preserving technique. Other customized options are the wrap around flap plus second toe proximal phalanx, twisted toe flap, pollicised index finger stump plus wrap around flap, pollicised index finger stump plus lateral arm flap, pedicled groin flap plus toe transfer, osteocutaneous lateral arm flap, and transfers containing epiphyseal plates.

Options for Finger Reconstruction

The number and location of digits in the reconstructed hand should be carefully planned.

Single finger amputations are rarely reconstructed unless the patient has a critical need for all five digits (e.g., some musicians).

Guidelines have been published for reconstructing multiple finger amputations. It is recommended that at least two adjacent fingers are reconstructed for chuck pinch, increased stability and wider span of grasp. The determination of which fingers to reconstruct can be a difficult decision. In general, laborers requiring power grasp should have two ulnar digits. In others, where fine manipulation is more important, reconstruction of two radial digits is advised.

Second toe transfers are primarily employed for finger reconstruction, but the third toe can also be used. When two toes are to be transferred to a hand, the surgeon has to decide whether to use two separate toe transfers, or a combined double toe transfer. There is no general agreement as to which option is better. In general, combined second and third toe transfer is used to reconstruct two digits which have been amputated proximal to digital webs. Two separate second toe transfers are usually recommended for digits amputated distal to their intervening web space. Foucher maintains that en bloc transfers of second and third toes provides better range of motion than two separate second toe transfers. Using two separate toe transfers avoids the syndactylous appearance seen after combined double toe transfers.

In addition to toe transfers, microsurgical finger transfers are also an option to be considered. The cross hand ring finger transfer procedure uses the ring finger from the opposite normal hand as the donor digit. This operation has not achieved widespread popularity because of its donor site morbidity.

A number of other unusual microsurgical cross hand finger transfers have occasionally been used for thumb and finger reconstruction. For instance, there are a few reports of damaged or abnormal digits being transferred from the opposite hand. These include the transfer of previously injured digits, and the transfer of paralyzed digits. In a similar way, the use of polydactylous toes for digital reconstruction in congenital hand anomalies has also been described. In these cases, surgeons were presented with unusual opportunities because of unique situations in individual patients. Reconstructive surgeons should always be looking for unique opportunities of this kind.

Microsurgical Digital Reconstruction—Anatomy

Anatomically, the great toe most closely resembles the thumb. The lesser toes are more similar to the fingers in size, shape, and appearance. The great toe is about 20% broader than a thumb, with a wider but shorter nail.[1]

The relevant foot anatomy is graphically demonstrated in the anatomical drawings of Netter.[5] The metatarsophalangeal joints are condyloid and analogous to the metacarpophalangeal joints of the hand. Each joint is enclosed in a thick capsule which is reinforced by the extensor tendon expansion dorsally. In the lesser toes, the plantar ligament (a volar plate analog) is a fibrocartilagenous plate that originates from the metatarsal head and firmly attached to the proximal plantar border of the proximal phalanx. On the medial and lateral aspects of the metatarsophalangeal joints, collateral ligaments assure stability. In the great toe, the plantar ligament is replaced by the two sesamoids and their interconnecting ligament. The deep transverse metatarsal ligaments interconnect the plantar ligaments and can be used as landmarks to help localize the dorsal metatarsal artery.

The interphalangeal joints of the toes share many of the anatomic arrangements seen in the metatarsophalangeal joints. However, unlike the metatarsophalangeal joint, which is capable of flexion, extension, adduction, abduction, and circumduction, the interphalangeal joint is limited to only two degrees of freedom, flexion and extension.

On the dorsal aspect of the foot, there is very little subcutaneous fat. There are two sets of extensor tendons: those to the lesser toes and those to the great toe. The extensor digitorum brevis, the only muscle covering the dorsum the foot, underlies the extensor digitorum longus tendons, and its tendons, together with the long toe extensors, form the dorsal expansion of the lesser toes at the level of the metatarsophalangeal joints. The extensor hallucis longus and hallucis brevis insert into the base of the proximal and distal phalanges of the toes, respectively, without forming an extensor expansion.

The muscles and tendons on the plantar aspect of the foot can be divided into layers. The most superficial layer consists of the flexor digitorum brevis, abductor hallucis, and abductor digiti minimi. The flexor digitorum brevis originates from the plantar aponeurosis and the medial calcaneal tubercle and inserts onto the middle phalanges of the lesser toes. The abductor hallucis inserts into the medial aspect of the proximal phalanx of the great toe. The abductor digiti minimi inserts into the lateral aspect of the proximal phalanx of the little toe. A deeper muscle layer contains the long toe flexors and the lumbricals, which, as in those of the hand, take origin from the flexor digitorum longus. The flexor hallucis brevis, flexor digiti minimi brevis, and adductor hallucis are found one layer deeper. The short flexors to the big toe insert into the medial and lateral sesamoids. Arising from the metatarsals and inserting into the bases of the proximal phalanges, the interosseous muscles form the deepest layer of all.

A thorough knowledge of key microvascular anatomy is crucial for successful free tissue transfers. For great toe and second toe donor site dissections, the “key” anatomy is the origin and the course of the first dorsal metatarsal artery. Unfortunately, the course of this artery varies greatly from individual to individual.[1,6] The first dorsal metatarsal artery is one of the branches originating from the dorsalis pedis, a continuation of the anterior tibial artery. On the dorsal aspect of the foot, the dorsalis pedis lies lateral to the extensor hallucis longus, and deep against the navicular and the medial cuneiform and their associated ligaments. It is accompanied by two venae comitantes, with the medial branch of the deep peroneal nerve just lateral to it. Just proximal to the first intermetatarsal space, the dorsalis pedis gives off an arcuate branch which subsequently gives rise to the dorsal metatarsal arteries of the lesser toes. At about the proximal first metatarsal space, the dorsalis pedis artery divides into the deep plantar and the first dorsal metatarsal arteries. As will be discussed later in the surgical technique section, this anatomic location of these two terminal branches of the dorsalis pedis is the basis of the rationale for retrograde dissection of the vascular pedicle in toe harvesting.[4]

Leung et al[6] described cadaveric dissections in which seven anatomic variants in the course of the first dorsal metatarsal artery were found within the first intermetatarsal space. In type I variants (28.6%) there was a superficial first dorsal metatarsal artery. In type II variants (25.7%) there was an intramuscular first dorsal metatarsal artery. In type III variants (20%) there was a deep first dorsal metatarsal artery. The type IV pattern (7%) had both deep and superficial first dorsal metatarsal arteries. In type V variants (11.4%) the first dorsal metatarsal artery was absent and the deep plantar artery was the only terminal branch of the dorsalis pedis system. Type VI specimens (1.4%) had no first metatarsal arteries—dorsal or plantar. In type VII cadavers (5.7% cases), the dorsalis pedis artery was completely absent. Fortunately, type VI and VII patterns were very rare.

Proximal to the intermetatarsal ligament, the first dorsal metatarsal artery sends a branch to form the medial digital artery to the great toe, and distal to the ligament, it bifurcates form branches that supply the lateral and medial aspects of the big and second toes, respectively. The neurovascular bundles in the toes, as in the fingers, lie just plantar to the mid-axial line, with the lateral digital artery of the big toe generally larger than the medial one.

Microsurgical Digital Reconstruction—Surgical Technique

Donor Site Dissection Techniques

Great Toe Harvesting Technique

Dissection is carried out under tourniquet control. The ipsilateral toe is usually selected. The limb is partially exsanguinated so that the vessels can be readily identified. The skin incision is planned to create distally-based dorsal and plantar triangular flaps at the level of the metatarsal phalangeal joint. The dorsal flap is planed such that it follows the course of the distal portion of the dorsalis pedis artery and the first dorsal metatarsal artery. In general, it is better to harvest less skin from the foot to allow primary closure of the donor site, as skin grafts are take better in the hand.

The dorsal skin flap is first elevated and the subcutanous veins should be identified and protected. The superficial peroneal nerve can be found in the operative site just superficial to the extensor retinaculum at the midportion of the first metatarsal. It should be identified and protected. Next, the extensor hallucis brevis and longus are identified and dissected to the appropriate lengths. Immediately under the extensor hallucis brevis, just proximal to the first metatarsophalangeal joint, the deep peroneal nerve and the dorsalis pedis artery and its venae comitantes can be found. The deep peroneal nerve should be included in the transplant for later attachment to the dorsal radial sensory nerves. Dissection of the pedicle can continue in a traditional antegrade fashion, tracing the dorsalis pedis artery from proximal to distal to identify the first dorsal metatarsal artery. This vessel is then followed into the first web space, to the point where it bifurcates to form the proper digital arteries of the toes (about 6-7 cm). As noted previously, the course of the first dorsal metatarsal artery can vary greatly. If the artery remains superficial, the dissection can be straight forward. Beware, however, that in many cases, the vessel will dive into the first dorsal interosseous muscle, or even deep to it, making dissection much more challenging. In cases where the dorsal metatarsal artery is vestigial or absent, the common digital vessel, locating plantar to the deep transverse metatarsal ligament, must be dissected out. This dissection may be simpler to carry out through a plantar incision. In this situation, to avoid extensive dissection into the plantar aspect of the foot, only about 3 or 4 cm of the common digital vessel should be dissected out. The pedicle can be extended with a vein graft.

In an attempt to avoid the situation in which dissection of the dorsalis pedis is carried out early in the operation only to discover that the first dorsal metatarsal artery is either inadequate or absent, Wei et al[4] advocate retrograde dissection of the vascular pedicle. Instead of starting the dissection proximally, at dorsalis pedis artery, the authors start their dissection in the first web space. Dissection is then carried out in a proximal direction, dorsal and plantar, for about 1-2 cm. If the first dorsal metatarsal artery is not identified dorsal to the deep transverse metatarsal ligament, or if it is inadequate, then the dissection proceeds plantarly, isolating the first (deep) plantar metatarsal artery for use as a vascular pedicle. Use of a vein graft in this situation is advisable to avoid extensive dissection into the plantar aspect of the foot. Wei describes several advantages with his retrograde dissection techniques.

In particular, he points out that identification of the toe's dominant blood supply earlier in the procedure avoids unnecessary dissection of an inadequate pedicle.

Once the vascular pedicle has been prepared, the digital nerves and flexor tendons can be dissected through the plantar incision. The common digital nerve should be carefully dissected free from the surrounding soft tissues to produce a nerve pedicle that can be readily sutured to the common digital nerve in the hand. An osteotomy though the proximal phalanx, or a metatarsophalangeal disarticulation is then made. An oblique osteotomy through the first metatarsal head has been described as a method for reducing metatarsophalangeal joint hyperextension, which is undesirable after the toe has been transferred to the hand. Wei recommends leaving about 1 cm of proximal phalanx in the big toe to avoid disturbing the foot biomechanics.

Prior to completely detaching the toe, the tourniquet should be released to confirm that there is intact vascularity to the toe and skin flaps.

The Wraparound Flap

It has been devised for improving appearance of the reconstructed thumb thus giving the possibly to create a «custom made» new thumb.

This is feasible through a combined tissue flap including part of the distal phalanx with the corresponding part of the nail, an extended flap with dorsal and plantar skin narrowed down to the size in which the soft tissue flaps can wrap it around. No joint or epiphysis is incorporated and has no growth potential. Therefore this procedure is not indicated in children. It is also a prerequisite for the stump to have a functioning MCP joint if we want to retain mobility of the reconstructed thumb (Fig. 9.1).

The wraparound procedure is performed in four steps. First, after measuring the length and the circumference of the normal thumb and the size of its nail, we transfer these dimensions on the lateral side of the ipsilateral toe. The incisions are marked on the skin and the nail, and the cutaneous strip is left on the medial side of the great toe.

Secondly the dissection starts at the dorsum of the foot with identification of the dorsalis pedis artery. Then, following its course it descents down to the first dorsal metatarsal artery until it reaches the base of the great toe. Following, the skin flap is dissected and detached from underlying tissues as a degloving, including the digital nerves and the whole nail phalanx.

Particular attention should be paid to avoid disruption of the germinal matrix at the dissection of the nail with the underlying bone. The dorsal venous system should also be protected into the dorsal skin flap. At the donor site, the paratendon should be retained on the extensors thus allowing coverage with skin grafts.

The final wraparound transplant should include a composite tissue flap made out of the most part of the great toe skin, nail and distal phalanx with a dorsal venous system, two digital nerves and the lateral digital artery as an extension dorsalis pedis and the distal branches of the dorsal peroneal nerve (Figs. 9.2 and 9.3).

To create a «custom made» thumb, a tricortical bone graft from the iliac crest is harvested sized and shaped up so that the length of the contralateral thumb is accomplished. The skeleton of the new thumb will be completed now with the base of the 1st phalanx proximally, the trimmed part of the distal phalanx of the great toe distally and an interposed graft from the iliac crest. Adequate fixation with either 2 K.

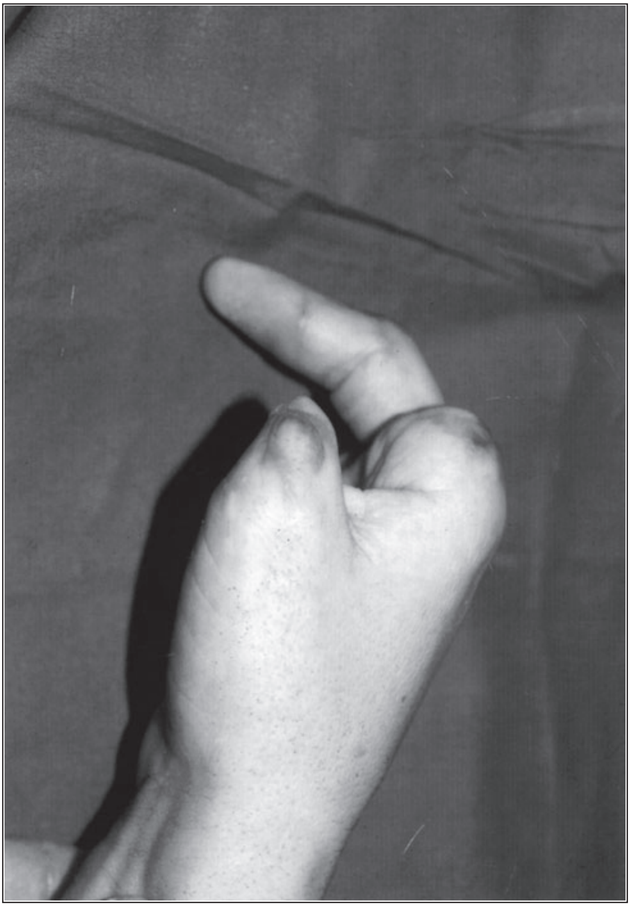

Fig. 9.1. Thumb amputation near the base of the 1st MCP.

wires or miniature plates and screws, is necessary to secure stability until bone healing and graft incorporation is achieved

The nail of the transplant also needs trimming until its size approximates the contralateral one. The nerves, veins and arteries are suture to the previously prepared recipient site structures and finally the skin is closed. The paronychial skin folds at the radial side of the transplant is shaped and sutured with the skin edge inverted towards the nail edge thus covering its radial side (Fig. 9.4 and Fig. 9.5).

Closure of the Donor Site after Dissection of the Wraparound Flap

The remaining skin at the medial side of the donor great toe is inadequate to cover the soft tissue defect. We prefer to shorten the remaining skeleton down to the middle of the 1st phalanx so that this skin flap covers the distal and the plantar aspect

Fig. 9.2. Preparation of the recipient site and extension of the skeleton with an iliac crest bone graft sized and shaped according to the dimensions of the contralateral thumb.

of the stump. A thin full thickness skin graft covers the dorsum and the lateral site of the substantially shortened great toe. With this technique, the need for a cross finger skin flap from the second toe is avoided.

Trimmed great toe offers an alternative solution for thumb reconstruction that avoids the bulk of the whole great toe, and provides the reconstructed thumb with some motion in the IP joint unlike the wraparound. The dissection of the trimmed

Fig. 9.3. Wraparound flap dissected from the ipsilateral great toe, perfused after release of the tourniquet.

great toe is more demanding but gives a much more appealing appearance to the reconstructed thumb.

Second Toe Harvesting Technique

The technique of harvesting the second toe is similar to that of the great toe. The main difference is that in the lesser toe, the metatarsal can also be taken if greater length is desired for digital reconstruction. V-shaped dorsal and volar incisions are used, with their apices proximal and centered on the second metacarpal. Dissection of the neurovascular bundle is identical to that of the great toe. The dorsalis pedis artery is traced distally. Depending on which arterial system is dominant, the first dorsal metatarsal artery or the plantar metatarsal artery is used, with its branches to

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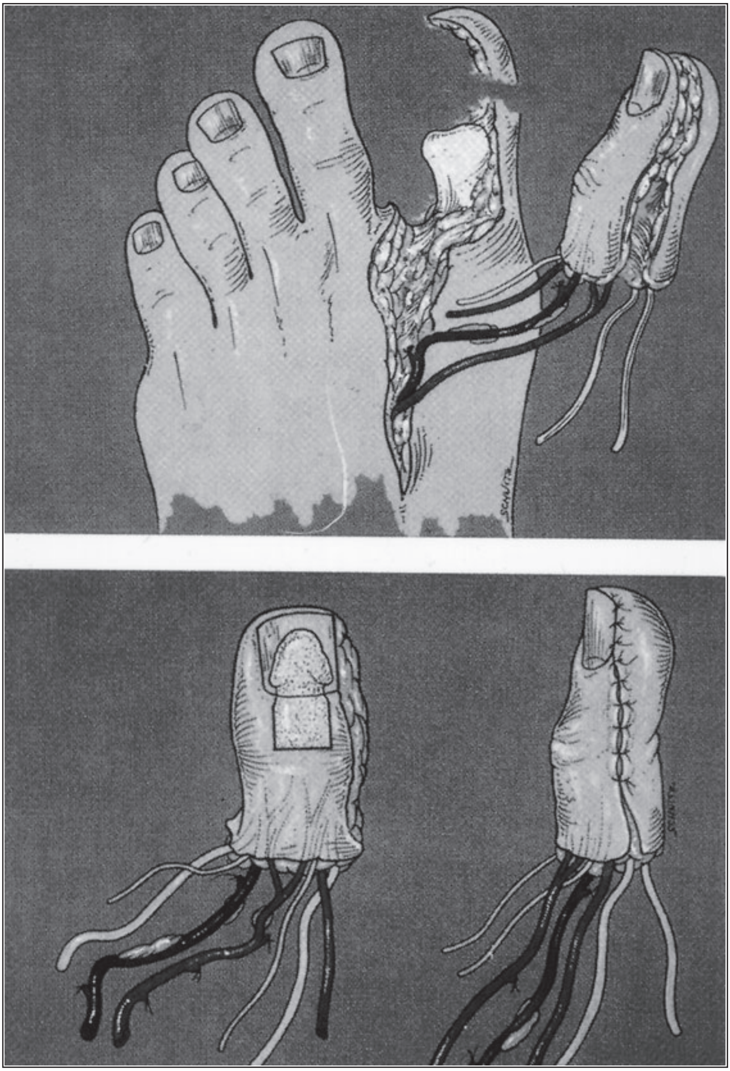

Fig. 9.4. "Custom made" thumb reconstruction with wraparound flap.

the second toe. The dorsal veins, along with branches of the superficial and deep peroneal nerves to the second toe, are prepared. If desired, these dorsal sensory nerves can be coapted to branches of the superficial radial nerve, at the recipient site. Dissection of the toe extensors, flexors, and digital nerves are also done in a manner similar to that described for the great toe.

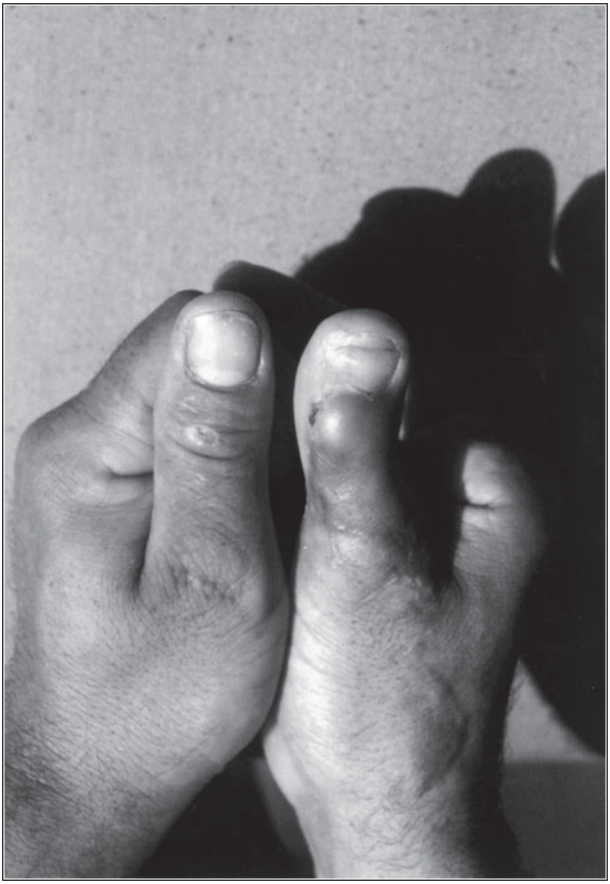

Fig. 9.5.

Recipient Site Dissection Technique

In order to minimize surgical and ischemic time, it is recommended that recipient site preparation is done by a second surgical team simultaneously with the toe harvesting procedure. A pneumatic tourniquet is used to provide a bloodless field for dissection. Incisions, at the recipient site, are often dictated by scars from previous wounds. The thumb is usually prepared with fishmouth incisions, using either dorsal/volar or lateral longitudinal incisions to raise the skin flaps. Exposures of the bone, dorsal veins, flexors, extensors, radial cutaneous nerve, digital nerves, and radial artery are done with minimal dissection to avoid devascularising the skin flaps. In the case of a second toe transfer which has triangular skin flaps in the dorsum and the volar aspect, a dorsal/volar incision on the thumb stump is preferred to accommodate the transplant and also to provide side coverage with the recipient skin flaps.

Transplantation and Tissue Repairs

Transplantation is done in a sequence which progresses from coarse to fine work: skeletal fixation, flexor tendon repair, extensor tendon repair, arterial anastomosis, venous anastomosis, and nerve repair. Various methods of osteosynthesis have been described, including single K-wire, crossed pins, and intraosseus wires. Tendon repairs, if possible, should be done at the level of the wrist. The arterial anastomosis can be done at one of several different locations. Veins are anastomosed to one of the large tributaries, which drain the dorsum of the hand. Digital nerves are repaired as carefully as possible, using an epineural technique. Toe-to-thumb transfers are usually revascularized to the radial artery. The ulnar artery may be used when toes are used for digital reconstruction on the ulnar side of the hand. Central digits may be anastomosed with the radial artery, ulnar artery, palmar arch, or common digital arteries.

Postoperative Management

At the end of the procedure, a bulky, nonconstrictive dressing is put around the forearm and hand. This is covered with a light plaster cast, constructed so that there is easy access for the transferred toe to be observed and monitored. When the dressings are applied, care should be taken to avoid compression.

Toe transfers are particularly susceptible to vasospasm.[7] After leaving the operating room, the patient is nursed in a warm room, which is free of draughts. Exposure to cigarette smoke is not allowed, and food or drink containing caffeine should be avoided . The hand is elevated with the flexed elbow on a pillow. It is important to avoid hypotension and to maintain good circulatory volume to ensure that peripheral perfusion is not lost.

Postoperative monitoring is done with clinical observations and skin temperature measurements. Temperature probes are placed on the tip of the toe and on the tip of an adjacent digit, which acts as a control. The transferred toe is initially checked half hourly. Color, capillary refill, turgor, and temperature are monitored. The nurse charts the findings and alerts the medical staff if changes occur. Swelling, increased turgor, increased speed of capillary refill, and a bluish coloration indicate a venous outflow problem. Decreased turgor, decreased temperature, slow or absent capillary refill, and a pale color indicate arterial insufficiency. Changes are acted on quickly, because early hemodynamic changes may progress to anastomotic thrombosis. Patients are not routinely anticoagulated, but systemic anticoagulation is used in cases where there have been anastomotic problems.

The patient is kept in bed for the first 4 or 5 days. This reduces circulatory variations in the hand, and allows undisturbed wound healing to start at the foot donor site. The bulky postoperative cast is removed once the transferred toe is hemodynamically stable and the wounds are healing. This is usually 5-10 days in adults and 2-3 weeks in children. After the cast is taken off, the hand is placed in a protective splint, and the patient starts hand therapy. The hand therapist initially priorises restoration of function in the unoperated part of the hand. When enough bone healing has taken place, the K wires are removed and range of motion exercises are started in the transferred toe(s). Resistance exercises and strengthening are done later, when bone union has occurred and range of motion has been restored. Functional activities are started as soon as the hand is capable. Sensory reeducation is important and is done when there are signs of nerve regeneration.

Microsurgical Digital Reconstruction-Results

Functional Results

Sensory Recovery

Recovery of sensibility may take a year or more and is likely to be incomplete in older patients.[8,9] Sensory recovery is maximal at two years. Two point discrimination is less than 10 mm in approximately half of patients. Nearly all patients eventually develop protective sensibility.

Kay et al tested static two point discrimination in children that had undergone second toe transfers at 9 months to 14 years of age.[10] Testing was felt to be reliable in 75% of children and found to be an impressive mean of 5 mm. They found no statistical correlation between the two point discrimination and the number of digital nerves repaired. All transfers recovered protective sensibility. They hypothesize that the high quality of sensory return may be one of the many advantages performing surgery at an early age.

Motor Recovery

Range of motion following toe transfers is quite variable, but nearly all patients develop some degree of active range of motion. Transferred toes generally have greater passive motion than active motion. Kay et al found the total active range of motion was not related to the total number of flexor tendon repairs.[10] However these results are based on children and are all second toe transfers. However, these results are based on children and are all second toe transfers. Most surgeons repair all donor tendons.

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After great toe to thumb transplantation, radial and palmar abduction have been reported to be within 10° of normal with near normal flexion to the base of the small finger. Interphalangeal joint active range of motion averages 29°.[1]

The great toe transfer has been shown to provide 36% of the baseline thumb strength compared to approximately 16% for the second toe transfer. Strength is improved with the presence of thenar muscles.[11] In isolated thumb loss and reconstruction, grip strength is 80-100% of the contralateral normal thumb and key pinch 65-169% of the opposite side.

Growth in Children

Expected growth in toe to thumb transplantations in children has been reported to be in the range of 60-100% of normal.

Aesthetic Results

The second toe appears longer on the hand and better approximates the appearance of a finger. The bony length of the toe is masked by the web space riding more distally on the foot. Kay found that 90% of children felt that the hand looked better than preoperatively.[10] The great toe approaches the appearance of the thumb more than the second toe, especially with the wrap around technique which is discussed in another Chapter.

Psychosocial Well-Being

Children seem to adapt well to toe transfers. Parents (84%) and children (88%) felt that the appearance and function of the hand was 'improved' to 'very much improved'.[10] Most parents noted that their child was incorporating the toe transfers into daily activity 'most of the time' to 'all of the time'. Both parents and children were unconcerned with donor site aesthetics. All parents were glad that their child had undergone the second toe transfer.

There are no reports of formal psychological testing in adults, but patients are usually satisfied with toe-to-hand transfers, especially if their function is improved.

Donor Site Results

Harvest of the second toe leaves the most aesthetic results and nearly imperceptible functional loss. Combined second and third toe transfers result in increased load on the great toe and heel, however patients rarely complain of any functional abnormality. The hallux has the prominent weight bearing function and when harvested, the second and third metatarsal heads bear the load. Frykman found that patients were able to walk and run without difficulty.[11] These results show that functional loss in the foot should not be a consideration in regard to surgical options, providing that the donor site dissection is carefully planned and executed.

Microsurgical Digital Reconstruction—Complications

Surgical Complications

Vascular compromise occurs in 10-15% of toe transfers.[7] The most common vascular complication is vasospasm. This usually occurs in the first few days postoperatively. If removing skin stitches and using heat lamps and/or vasodilators do not relieve the vasospasm within an hour, the anastomosis should be re-explored. Most transfers can be saLVAged, however approximately 3.5-5% go on to fail. Venous thrombosis is less common, but also prompts re-exploration. Venous thrombosis is likely the result of poor surgical technique or hematoma.

Partial necrosis of thin toe skin flaps is common. If neurovascular structures or tendons are exposed, early intervention is necessary to prevent desiccation using local tissue transfers or skin grafts.

Free toe transfer is subject to the same postoperative complication of infection. Perioperative prophylactic antibiotics, usually cephalosporins, are recommended. If leeches are used for venous congestion, antibiotic coverage of Aromonas hydrophilia is warranted.

Functional Complications

The main reason to perform a toe to hand transfer is to improve and function. It is disappointing when results do not approach expectations. Secondary procedures to improve functionality are required in up to 20% of cases of transfers.[2] The most common functional complication is tendon adhesion, which must be differentiated from stiffness. In Wei and Yim' s study[12] of 133 toe to hand transfers, tenolysis was the most common secondary surgery (7%), followed by arthrodesis and web space deepening. Flexor tenolysis is especially useful. Stiffness is best treated with aggressive hand therapy. Function may also be improved with various tendon transfers as deemed necessary, most frequently opponensplasty.[1]

Malalignment requiring rotational osteotomy is less frequently required as the surgeon becomes more experienced in toe transfer technique. Poor sensory return must be taken in context with the age of the patient, but may require nerve grafting. These patients are more susceptible to burns until protective sensation develops.

Donor Site Problems

The most common complications of the donor site are hypertrophic scarring and hypersensitive scars. Patients that have undergone hallux harvest have complained of inability to wear thongs and heavy boots. Very rarely, a patient who has undergone great toe transplantation will experience difficulty walking or running normally.

Secondary Procedures

Secondary procedures[12] may be necessary to improve the results of toe-to-hand transfers. In addition to the secondary procedures mentioned above, aesthetic refinements are commonly done and include pulp-plasties, scar revisions, and Z-plasties.

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Reconstruction of Large Skeletal Defects of the Extremities with:

A. The Free Vascularized Fibula Graft

K. N. Malizos, Ch.G. Zalavras, Zoe Dailiana, A. Beris

Introduction

A skeletal defect represents loss of osseous tissue, which alters to a variable degree the anatomy and architecture, the biomechanical properties and the functional ability of load transfer of the affected bone. A skeletal defect is considered critical when it is of such dimensions that it cannot be spontaneously restored by the intrinsic healing process and necessitates surgical intervention and augmentation of the healing process.

Skeletal defects can be classified according to their etiology as *primary* or *secondary. Primary* bone defects result from high-energy trauma, which can produce an open fracture with extensive soft tissue damage, osseous comminution and even extrication of bone fragments. *Secondary* defects result from excision of pathological tissue. Pathologic processes involving the skeleton may be congenital, as in congenital pseudarthrosis of the tibia, or acquired, as in aseptic and septic nonunions, osteomyelitis and bone tumors.

Large skeletal defects constitute a difficult challenge for the surgeon and a source of significant morbidity, functional impairment, and economic, psychological and social distress for the patient.

Detailed evaluation of each case will disclose the elements on which the treatment plan will be based. It should include assessment not only of defect parameters, such as location and dimensions, but also of the soft tissue envelope condition, the limb length and alignment, the adjacent joint range of motion, the presence of associated injuries and the patient's functional requirements and general health condition.

In many cases where most of these parameters are not favorable the surgeon is confronted with a critical decision, that is to salvage or to amputate the limb. Although this dilemma appears frequently in clinical practice, the complexity of the situation due to the interplay of multiple patient and local extremity factors (age, hemodynamic status, skeletal, soft tissue, vascular and nerve injury) may pose difficulty in reaching a decision.

Reconstruction of skeletal defects has been attempted with a variety of treatment methods. Since the first report by Job Van Meeckeren in the 17th century of bridging a human skull defect with a canine graft, the surgeon's armamentarium has considerably expanded to include several biologic techniques (bone grafts, bone

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substitutes, growth factors and distraction osteogenesis), as well as endoprostheses implantation.

Vascularized bone grafting was first attempted in 1905 by Huntington, who transposed the ipsilateral fibula as a pedicle graft for reconstruction of a tibial defect. However, it was not until 1975, that free transfer of a vascularized fibular graft using microvascular techniques became possible and was reported by Taylor et al.

Vascularized bone grafts from other donor sites have been utilized, mostly from the iliac crest and the rib, but also from the scapula, humerus, radius, tibia and second metatarsal. However, the free vascularized fibular graft (FVFG) is the one that has found the most widespread application in the management of large skeletal defects and will be reviewed in detail.

The free vascularized iliac crest bone graft is an other alternative also utilized in a number of applications where its morphological characteristics fit better.

Graft Properties

The FVFG has distinct morphological and biological properties, as well as a unique versatility, which confer several advantages, when it is compared to conventional avascular grafts or vascularized grafts from other donor sites.

Anatomy

The fibula is a cortical bone that can provide a free graft of length up to 30 cm in tall individuals, raised on a vascular pedicle that consists of the peroneal vessels.

The FVFG provides a strong cortical strut for defect reconstruction that can reach a significant length. The straight configuration and the anatomic size and shape of the fibula make it match exactly the forearm bones and fit into the medullary canal of the humerus, the femur and the tibia. Therefore, it constitutes an ideal graft for extremity reconstruction.

The peroneal artery, accompanied by the 2 peroneal veins, stems 3-4 cm distal to the anterior tibial artery origin and follows a course parallel to the fibula lying between the flexor hallucis longus and posterior tibialis muscles. The diameter of the peroneal artery and veins is 1.5-2 mm and 2.5-4 mm, respectively.

The FVFG has dual vascularity, which it derives mainly from endosteal but additionally from periosteal sources. The endosteal blood supply is based on the nutrient artery, which stems 6-14 cm from the peroneal artery bifurcation, enters the middle third of the diaphysis via the nutrient foramen and then is divided into an ascending and a descending branch. In about 1% of people there are 2 nutrient foramina, however in 4% none is identified. The foramen is located within 2.5 cm of the mid-diaphysis, close to the medial edge of the posterior aspect of the fibula. The periosteal blood supply is derived via 8-9 periosteal branches, mostly in the middle third of the diaphysis.

Biology

The FVFG after the anastomosis of the pedicle vessels follows a different sequence of biological events compared to avascular grafts. The process of creeping substitution, which involves necrosis of the graft, resorption and then new bone formation, is bypassed. There is decreased resorption and mechanical weakening of the graft, osteocytes remain viable and osteoblastic activity is immediate and enhanced, because of the good vascularity. Incorporation of the graft depends only on healing of both graft-host junction sites and is equivalent to union of a segmental fracture.

Therefore, the viability of the graft maintains its mass and prevents alteration of its architecture, renders the graft biomechanically stronger than an avascular one and enhances healing and hypertrophy. Moreover, the FVFG is an important source of vascularity in cases of scarry and avascular recipient sites.

Versatility

The combination of these morphologic and biologic properties renders the FVFG a truly versatile flap that can be tailored to suit the need of the individual case. Both the configuration and the composition of the graft may be modified.

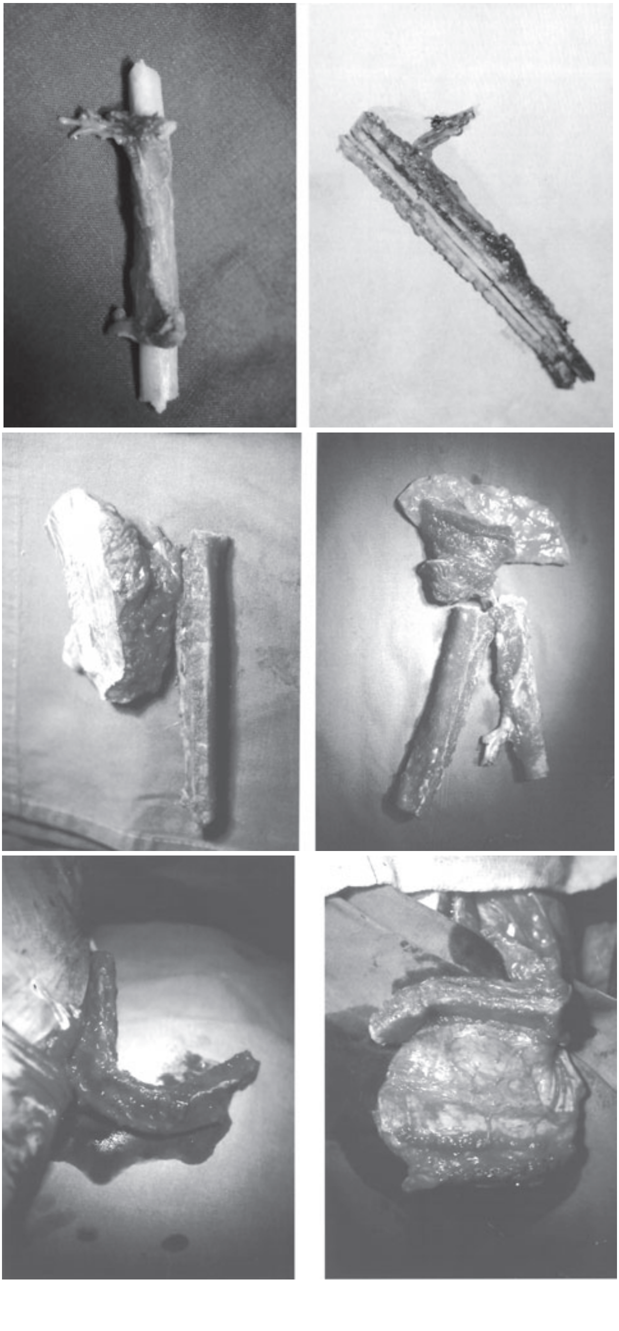
The FVFG can not only be used in its naturally straight configuration, but due to its dual vascularity it can undergo a variety of osteotomies. Specifically, it can be transversely osteotomized in the middle of the diaphysis in order to produce 2 cortical struts on a single pedicle (double barrel) to reconstruct the femur or tibia. It can be transversely osteotomized in multiple sites to resemble the shape of the mandible and, moreover, it can be longitudinally osteotomized to create an open-book configuration with increased surface of vascularized bone as an adjuvant to the healing process. Simultaneous transfer of 2 FVFG, although technically demanding and time consuming, can reconstruct femoral defects up to 30 cm of length, without the extended time necessary for hypertrophy of a single FVFG.

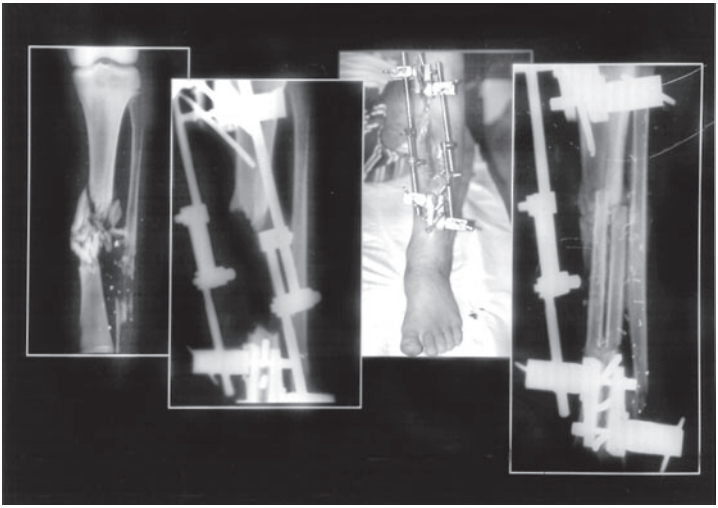
The composition of the graft can vary according to the defect requirements. Defects may be classified as osseous, when there is only bone loss, or composite, when an additional soft tissue defect is present. Transfer of skin, fascia, muscle, or combinations of these can accompany the FVFG, as well as transfer of the growth plate of the proximal fibular epiphysis.

A *skin paddle* of dimensions up to 20 x 10 cm can be simultaneously transferred, based on perforating fascio-cutaneous branches at the middle and distal third of the pedicle, to facilitate coverage and, more importantly, to *monitor patency* of the pedicle anastomoses. Part of the soleus muscle or the flexor hallucis longus can be included in the flap to reconstruct soft tissue defects and cover otherwise exposed bone. The artery of the soleus branches immediately distally to the origin of the peroneal artery and can be included in the pedicle. Moreover, transfer of the proximal epiphysis permits reconstruction of defects involving the physis and allows for longitudinal growth of the graft in children.

Therefore, the FVFG can be transferred not only as an *osseous* flap but is very versatile and may serve as a *composite* as well, to simultaneously reconstruct a skeletal, soft tissue and growth plate defect (Figs. 10A.1 and 10A.2).

Fig. 10A.1, right. The osseous flap is versatile and according to the needs of the defect at the recipient site could be given different configuration, i.e., take the shape of a mandible with multiple osteotomies, split longitudinally, cut in half and folded as a double barrel graft, plain or composite with skin and muscle for simultaneous coverage of soft tissue defects.





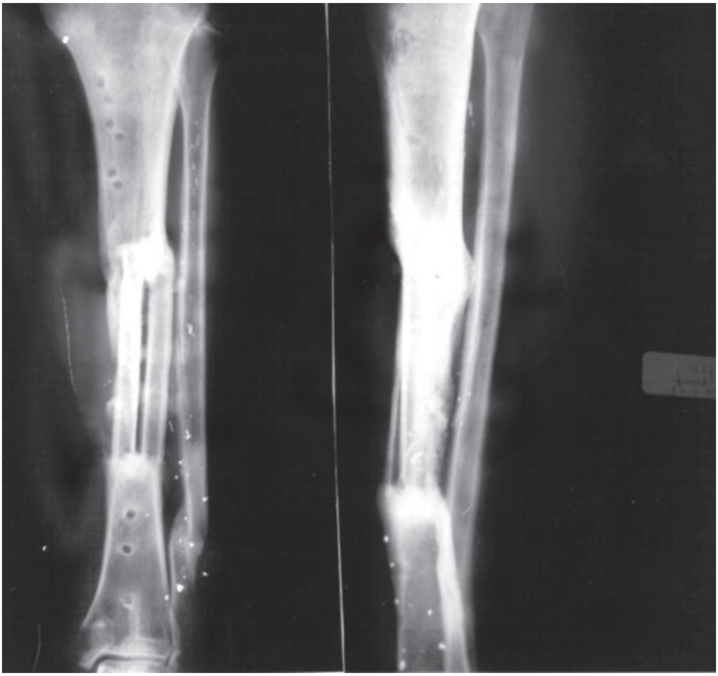


Fig. 10A.2. An open tibia type IIIb fracture with compound loss of tissues, after debridement, external fixation and reconstruction with a folded free vascularized composite osseous flap with skin and muscle. The 9 cm defect is bridged both for length and width at the same stage. X-ray appearance after 18 months.

General Treatment Considerations

Indications

Transfer of a FVFG is a technically demanding procedure. The principal indication for use of this method in the reconstruction of skeletal defects is the inappropriateness of simpler techniques, such as avascular bone grafting. Therefore, a defect of length greater than 5-6 cm, poor and avascular surrounding soft tissues and need for longitudinal bone growth are conditions, which warrant use of the FVFG. Distraction osteogenesis can also be considered in these cases. However, maximum length gained is up to 14 cm, duration of treatment is prolonged, complications are frequent and patient compliance is a critical factor. In addition, longitudinal soft tissue defects cannot be simultaneously addressed.

Preoperative Planning

Detailed preoperative evaluation and planning are more than necessary. Evaluation should include defect, soft tissue, limb and patient factors.

The length of the defect must be accurately measured by radiographs, computer tomography or magnetic resonance imaging. These modalities will permit not only measurement of the existing defect but also estimation of the resection margins and the length of the defect that will result when pathological tissue is excised. The length of the defect in combination with the location will guide the surgeon to select the most appropriate graft configuration.

The soft tissue envelope is of paramount importance. Soft tissue defects can be reconstructed with transfer of composite FVFG with skin, fascia, muscle or combinations of these. However, not only the integrity, but equally importantly, the vascularity of the surrounding soft tissues should be assessed preoperatively. A history of high-energy trauma, infection, multiple previous procedures or irradiation suggests development of scar tissue, decreased vascularity of the soft tissue envelope, intraoperative difficulties and potential devastating complications for the unaware surgeon. The zone of soft tissue injury usually exceeds the dimensions of the skeletal defect. Scar tissue may extend well beyond the apparently injured area and involve the walls of blood vessels, compromising blood flow. In these circumstances, use of vein grafts may be warranted. Moreover, the possibility of previous arterial injury should be evaluated by clinical examination, Doppler assessment of flow and, if any doubt is present, with angiography.

The length and alignment of the limb should be evaluated so that correction of existing deformities be accomplished if possible. Nerve, muscle and tendon injuries and decreased range of motion of the adjacent joints will all adversely influence the final functional outcome, therefore their presence should be discussed with the patient and the management plan should take them into consideration. Additional procedures, such as nerve grafts, muscle transfers or joint arthrodeses may be needed to address these problems.

As in every major procedure, the patient as a whole should be considered. The functional impairment on the patient and its significance should be assessed. The general medical condition and suitability for prolonged and multiple operations, as well the willingness and the psychological, social and financial background are issues that should be addressed before embarking on a prolonged and demanding treatment plan.

If proceeding with the FVFG is the decision reached upon, then the donor site should be evaluated also. The maximum available length of the graft should be determined, the state of the fibula in cases of previous trauma should be assessed and anatomic deviations of the donor site vessels, that would endanger viability of the donor site, should be looked for. Presence of adequate pulses in both the posterior tibial and the dorsalis pedis artery and confirmation by Doppler examination is considered sufficient and routine angiography of the donor site is not advantageous.

Surgical Technique

The surgical technique involves three major phases: graft harvesting and preparation, recipient site preparation and transfer of the graft for reconstruction of the defect. Two operative teams simultaneously working on the donor and recipient sites can facilitate the procedure and decrease operative time.

Graft Harvesting and Preparation

A posterior approach for graft harvesting was originally described by Taylor, but the lateral approach, as described by Gilbert, has found widespread application. The plane between the peroneal muscles and the soleus is developed, the anterior compartment is entered and after osteotomies of the fibula, dissection of the graft and the vascular pedicle is carried out with release of the flexor hallucis longus and posterior tibial muscles. Proximal and distal osteotomies are performed at the appropriate locations to produce a graft of the desirable size. They are preferably done with a sharp bone-cutting instrument, to avoid thermal injury and the release of metal particles from the Gigli saw. Care should be taken to identify the posterior tibial vessels, which could be absent in the case of congenital variations or could be inadvertently mistaken for the peroneal vessels. The peroneal vessels should be identified, ligated and freed distally to avoid tearing the vessels away from the graft during the rotation maneuvers. In cases of composite graft harvesting, the dissection is modified accordingly to allow for incorporation of the soft tissue component. After exposing and freeing the origin of the peroneal vessel pedicle, the tourniquet may be deflated with the graft remaining in situ until preparation of the recipient site is complete, to reduce the total time of graft ischemia. If the recipient site is ready, the graft is harvested at this point.

Preparation of the graft includes microsurgical dissection of the pedicle and, when needed, osteotomy of the fibula to achieve the desired configuration. Specifically, it can be transversely osteotomized in the middle of the diaphysis in order to produce two cortical struts on a single pedicle (double barrel) to reconstruct the femur or tibia. Osteotomizing the fibula endangers the endosteal vascularity so in double-barrel fibular grafts, identification of the nutrient foramen with subsequent osteotomy in a way that the branch of the nutrient artery is not transected in the major segment has been proposed. The graft can also be longitudinally osteotomized to create an open-book configuration with an increased surface of vascularized bone as an adjuvant to the healing process.

If intramedullary insertion of the fibula is planned, we reflect the periosteum of both ends of the graft, so as to expose the inner, cambial layer of periosteum, containing mesenchymal cells to enhance bone formation during the healing process. Otherwise, we retain a periosteal sleeve around the graft that will be cuffed around the recipient bone.

Recipient Site Preparation

Preparation of the recipient site involves both the bone and the vessels. The skin incision should be carefully planned to facilitate exposure of the bone, dissection and anastomosis of the recipient site vessels with the graft pedicle, avoiding areas with compromised skin if possible. The pathologic lesion, whether fibrous nonunion tissue, sclerotic bone, necrotic and infected sequestra, tumor-invaded bone or congenital pseudarthrosis tissue should be resected to normal bone margins. The importance of adequate debridement cannot be overemphasized. Incomplete removal of avascular bone or pathologic tissue will hinder the healing process at the graft-host junction sites and will lead to recurrence in infection or tumor cases. In infection cases, debridement is usually undertaken in a separate procedure that precedes the final reconstruction. The bone ends that will receive the graft should be observed for bleeding, as an evidence of vascularity. It is noteworthy that the extent of bone involvement may be greater than anticipated from the imaging studies.

The integrity and condition of the recipient site vessels and their adequacy of pulsation should be carefully assessed intraoperatively, especially in cases with a scarry soft tissue environment. Direct damage at the time of the initial injury or involvement of the vessel walls by scar tissue will result in compromised blood flow. As a consequence, thrombosis and occlusion of the anastomoses may be facilitated and even viability of the extremity could be endangered, if the remaining collateral circulation is inadequate. The surgeon should be prepared to use vein grafts in order to perform the anastomoses at healthy vascular walls. In defects related to previous infection and presence of scar we can establish an AV shunt through a looped vein graft at the time of the first operation, when debridement is carried out. This technique allows placement of the anastomotic sites on normal vessels.

Defect Reconstruction

Bridging of the defect and stabilization of the fibula to the recipient bone and finally vascular anastomoses for revascularization of the graft comprise the final phase of reconstruction.

Stabilization of the fibula can be accomplished by a variety of osteosynthesis techniques. The ideal technique should respect and minimally compromise graft vascularity and provide sufficient stability to the host-bone-graft construct for promotion of the healing process, without being too rigid to avoid a stress-shielding effect on the graft. Osteosynthesis techniques that have been employed include plate, external and intramedullary fixation. Stability can be further enhanced with intramedullary insertion of the graft to the host bone, as in tibia, femur and humerus reconstruction. The addition of cancellous bone grafts at the junction sites can facilitate healing by its osteoconductive and inductive properties.

Selection of the best technique and implant should be individualized in each case, but general guidelines may be given according to location of the defect. In the upper extremity the size and shape of the fibula matches that of the humerus and especially of the forearm bones and good contact of the junction sites is possible.

Our experience with plate fixation in the upper extremity is quite favorable. Use of two smaller plates, one at each of the junction sites is preferable to a large plate spanning the entire length of the graft to minimize stress-shielding.

In the lower extremity, external fixation is the treatment of choice. It does not interfere with graft vascularity, it can provide adequate support without being too rigid and the elasticity of the fixation can be gradually increased by dynamizing the frame appropriately, therefore permitting the progressive transfer of load through the graft and promoting hypertrophy, according to Wolff's law. Moreover, by avoiding internal fixation implants, it facilitates wound closure and is particularly useful in infection cases.

Intramedullary fixation should not be routinely used, because it will result in damage of the endosteal graft vascularity. However, it could be of help in extended defects of osteoporotic bone not amenable to other fixation methods.

Vessel anastomoses are performed under loop magnification with 8.0 nylon sutures. The order of repair depends on the surgeon's preference. The veins are usually sutured first to reduce bleeding, but the arterial anastomosis could be performed first to minimize ischemia time. Arterial anastomosis can be performed in an end-to-side or in an end-to-end fashion. Vein grafts may be needed in cases of inadequate graft pedicle length or recipient vessel wall damage, which necessitates resection of the pathologic vessel wall to achieve anastomosis on healthy tissues.

Postoperative Follow-up

Postoperative follow-up can be divided to early, intermediate and late phases.

In the early postoperative period (up to 6 weeks), monitoring of the graft viability is unfortunately a difficult and unresolved issue. Simultaneous transfer of a skin paddle has been proposed as a means of immediate recognition of skin blood flow problems, which reflect the condition of the graft vascularity. Semi-invasive methods, such as implantation of flow meters or thermocouples on the pedicle or of laser probes into the bone, have not found widespread application due to their invasive nature and cost.

Radionuclide scanning with Tc^{99m} within the first week can disclose information on graft vascularity. Although timely recognition of anastomotic occlusion is not possible, the results of the study will be of prognostic significance and can help in postoperative management. High-resolution computerized tomography, MRI and single photon emission tomography have been proposed as monitoring modalities, but without a clear-cut advantage and at a higher cost.

In the intermediate period (up to 6 months) union of the graft-host junction sites is evaluated clinically and radiologically. Standard tomography and computerized tomography may also be of value. The time to union varies, depending on the age of the patient and the reconstructed bone. In our experience, approximately 3 months are necessary for incorporation of a graft in the upper extremity. In the lower extremity 4-5 months may be needed, with considerably earlier union, even in 2 months, in young patients operated for congenital pseudarthrosis of the tibia.

Use of the upper extremity should be restricted until the graft is incorporated. Thereafter, full function for everyday activities can be resumed with gradual heavier use. In lower extremity reconstruction only partial weight bearing should be allowed until incorporation of the graft. Then weight bearing can be gradually increased to promote hypertrophy of the graft.

In the late postoperative period the graft is observed for evidence of hypertrophy. In the lower extremity, hypertrophy of the graft to the point that it approximates the cross-sectional diameter of the host bone is a prerequisite for full weight bearing without support. Radiographs should be carefully assessed because different projections can lead to differences up to 15% in the diameter of the graft. Computer tomography will provide more accurate information and will demonstrate the simultaneous endosteal and periosteal hypertrophy of the fibula. The rate and the degree of hypertrophy will depend on the patient age, the host bone, the osteosynthesis method and the postoperative mobilization program.

The lengthy hypertrophy process can be bypassed with use of the double-barrel configuration of the graft. The two cortical struts on a single pedicle permit simultaneous reconstruction of both the length and the width of femur or tibia defects up to 15 cm. Longer femur defects can be reconstructed by transfer of two vascularized fibulas.

Complications

Reconstruction of large skeletal defects is a demanding process that is not without complications. Awareness of potential complications can lead both to early detection and treatment and more importantly to prevention. Complications may be classified as systemic or regional.

Systemic Complications

The inherent risks of general anesthesia, especially in patients with serious medical problems should never be forgotten, but instead minimized by careful preoperative evaluation. The lengthy procedure, which involves more than one operative site, can result in significant blood loss and hemodynamic instability of the patient. Deep venous thrombosis and pulmonary embolism should always be included in the differential diagnosis of leg pain and swelling, or chest pain and dyspnea, respectively.

Regional Complications: Recipient Site

Recipient site complications include compromised vascularity to the extremity, infection, nonunion of the graft-host junction sites and stress fracture of the graft.

Vascularity of the extremity to be reconstructed may be entirely dependent on the vessels that will be used for anastomosis with the graft pedicle. Failure to recognize this condition could lead even to loss of the limb.

Infection is a frequent complication in cases of septic nonunion or osteomyelitis and is related to persistence of microorganisms in inadequately debrided tissues. It can be superficial or deep and may necessitate irrigation and debridement, in addition to antibiotic treatment. The most important prevention measure is reconstruction in two stages, with initial debridement and antibiotic treatment, confirmation of resolution of the infection and then secondary transfer of the FVFG.

Nonunion of the graft-host junction sites is related to biologic and mechanical factors. Inadequate preparation of the host bone with persistence of disvascular ends, infection, and failure of the anastomoses are factors that compromise the biological basis of bone healing. Failure to sufficiently stabilize the graft-host construct will hinder union of the junction sites and graft incorporation.

Stress fracture of the graft is a frequent complication in lower extremity reconstruction, the incidence of which has been reported to be as high as 40%. Stress fractures usually appear during the first postoperative year and are related to excessive loading of an inadequately hypertrophied graft. This complication can be prevented by appropriate graft configuration, elastic fixation that will minimize stress-shielding, initial restriction of weight bearing and use of supportive devices, careful evaluation of the amount of hypertrophy by imaging modalities and progressive increase of loading, in accordance with graft hypertrophy. Under no circumstances should unrestricted full weight bearing be allowed before the graft attains the dimensions of the recipient bone. External support in form of a brace should be considered in noncompliant patients and especially in children.

Regional Complications: Donor Site

Donor site complications are not usually of major significance. A potentially devastating exception is compromised vascularity of the donor site when the anatomical variation of an absent posterior tibial artery is not detected preoperatively. The limb is dependent on the peroneal blood supply and harvesting of the graft might lead to loss of the limb, if the anterior tibial artery has a deficiency.

Transient weakness of the peroneal muscles and sensory abnormalities on the lateral aspect of the leg may be observed, as well as flexion contracture of the hallux, secondary to scarring of the FHL, which may require surgical release. Peroneal nerve injury, compartment syndrome and tibial fracture have been rarely reported.

Careful dissection, meticulous hemostasis and avoidance of suturing the fascia will minimize these already infrequent events. Retaining 6 cm of the distal fibula will prevent adverse effects on the distal tibiofibular syndesmosis and the ankle joint. The weight bearing capacity of the tibia is adequate and will compensate for loss of the fibula, which normally supports only a sixth of the transferred loads.

In skeletally immature patients harvesting of the fibula could lead to valgus deformity of the ankle joint, therefore tibio-fibular stabilization is recommended.

Specific Treatment Considerations

Trauma

Traumatic bone defects may be primary, as a consequence of an open fracture with bone loss, or secondary, after development of an aseptic or septic nonunion (Fig. 10A.3). Septic nonunions will be considered later under infection.

Several methods have been proposed for the management of primary traumatic skeletal defects. Some authors have implemented immediate radical debridement and reconstruction, within 72 hours from the traumatic incident. However, the consensus on this demanding problem appears to be early soft tissue coverage within the first 7-10 days, after serial debridement of the open fracture. Subsequently, reconstruction of the defect can be undertaken when a stable, well-vascularized and free from infection soft tissue envelope is present.

In long-standing aseptic nonunions, debridement of the fibrous tissue and avascular bone ends may increase an existing gap and result in a large secondary bone defect. In these cases, considerable difficulties may arise, related to previous vessel injury and to extensive scarring of the soft tissue envelope, as has been pointed out in the surgical technique discussion.

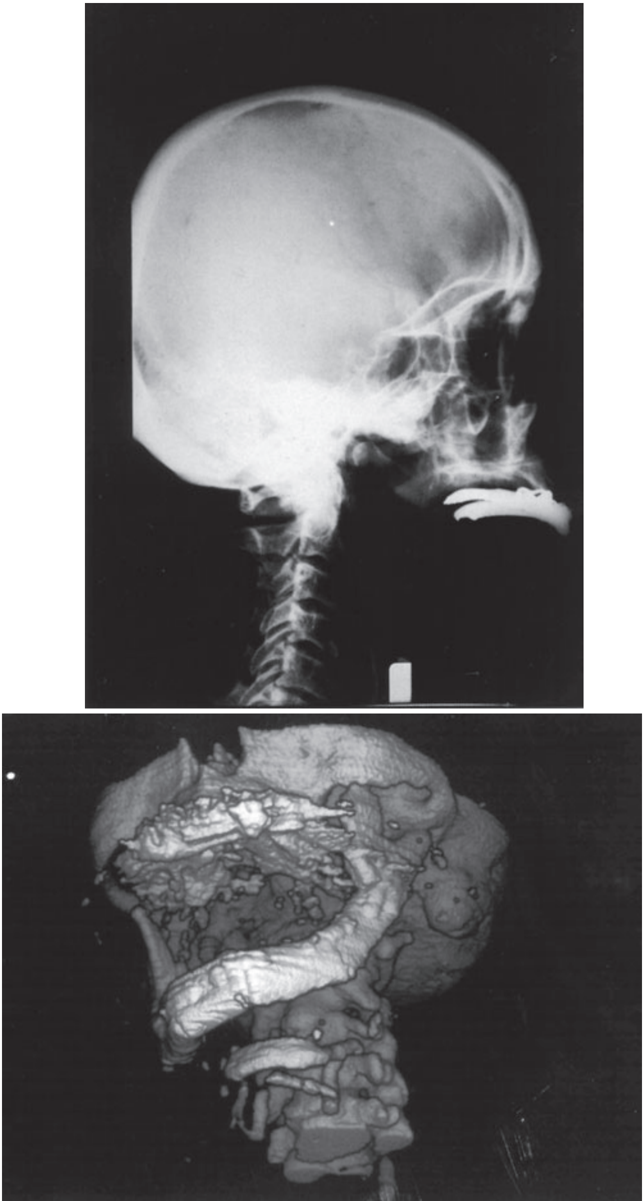


Fig. 10A.3. Complete loss of the lower mandible, and final appearance on a 3D imaging after reconstruction with a free vascularized fibula appropriately shaped with four osteotomies, to create the shape of the lower mandible.

Overall union rates greater than 90% have been reported in the absence of infection.

Infection

Bone defects associated with infection may result from osteomyelitis or septic nonunions. Management of these cases should focus first on infection eradication and then on reconstruction of the defect and comprises two stages.

The first stage aims to eradication of all foci harboring infectious organisms. Specifically, it consists of radical debridement with resection of all pathological tissue and removal of implants. Not only the microbial load is considerably diminished, but the barrier to the host defense mechanisms, which is formed by avascular and devitalized tissue (i.e., bone sequestra) and by biofilms on metallic implants, is removed. All resected tissues and removed implants should be cultured in an effort to identify the offending organism(s) and determine susceptibility to antibiotic treatment. Subsequently, polymethylmethacrylate (PMMA) antibiotic-impregnated beads can be placed in the resulting defect in order to deliver aminoglycoside antibiotics locally. In such a way, high local antibiotic concentrations can be achieved without the systemic toxicity associated with high blood levels. As an alternative, the defect can be bridged with a PMMA antibiotic-impregnated spacer. This has the additional advantage of maintaining the length of the bone and preventing contractures of the soft tissue envelope. Moreover, formation of a fibrous pseudo-capsule around the spacer is facilitated. This may be filled with cancellous autograft in addition to the FVFG to enhance the healing process. Stability of the deficient bone is provided by an external fixator, which is particularly useful in these cases.

A waiting period follows, in which antibiotic treatment is administered and the patient is monitored clinically, with laboratory examinations and imaging modalities.

Antibiotic treatment should be appropriate for the most common pathogens in the specific clinical setting, administered intravenously and modified, according to the culture and susceptibility results. *Staphylococcus aureus* is one of the most common infecting organisms in osteomyelitis, however in septic nonunions polymicrobial infection is usually the case with additional involvement of Gram negative organisms.

During this period, the patient should be carefully monitored for resolution of the infectious process. Inflamed overlying tissues should return to normal state, existing sinuses should stop draining and evaluation of laboratory indices, such as erythrocyte sedimentation rate, C-reactive protein and white blood cell count and differential, should disclose return to normal values. The waiting interval may last from 2-6 weeks. If improvement is not taking place, infection with unusual organisms should be considered. Tuberculosis, fungal and anaerobic infections could be the cause of resistance to treatment.

The second stage consists of reconstruction of the defect with the FVFG. The soft tissue envelope may be compromised with scarring and decreased vascularity, due to the infectious process. In this setting, the FVFG is of particular importance, since it enhances the blood supply of the recipient area. The already present external fixator can remain as the definitive form of osteosynthesis, to avoid the presence of implants in the recipient site. In the reconstruction of composite defects of the tibia of the forearm, a composite fibula and soleus flap provides adequate coverage in one-stage procedure.

Infection-related defects have a sub-optimal prognosis. Re-establishment of infection may occur and the healing process can be delayed or hindered, as has been reported in the literature, with overall union rates being lower in the presence of infection. Specifically, De Boer et al reported a 59% union rate in septic defects vs. 95% in traumatic defects without infection. Similarly, in the series of Han et al union was finally achieved in 76% of septic defects vs. 92% of aseptic ones. Our experience has given a 75% successful outcome in septic defects versus 95% in aseptic traumatic defects.

Congenital Pseudarthrosis

The FVFG offers significant advantages in the management of this challenging problem, which usually involves the tibia and in the past often resulted in amputation. It permits resection of all the pathological tissue, which otherwise would be hindered by the reluctance of the surgeon to create a large defect. Moreover, it facilitates reconstruction of the length and alignment of the affected bone. Excellent results have been reported by many authors with union in more than 90% of cases (Fig. 10A.4).

However, potential complications include recurrence of the lesion due to incomplete excision of the pathological tissue and stress fracture of the graft due to difficulty of compliance with restricted weight bearing in children. In addition, valgus deformity of the ankle could develop at the donor site. Fixation of the distal remnant of the fibula to the tibia has been suggested to prevent this complication.

The presence of neurofibromatosis should always be considered in a child presenting with congenital pseudarthrosis and the appropriate evaluation should be undertaken. Congenital pseudarthrosis of the forearm is quite rare, but the limited experience with FVFG management is favorable.

Femoral Head Osteonecrosis

Avascular necrosis of the femoral head is a potentially disabling clinical entity that is currently diagnosed with an increasing incidence most commonly in young adults. In the majority of the cases both hips are affected. The natural history of the disease leads to complete joint degeneration. Arthroplasty is not desirable in the young individuals and a real necessity for joint preserving procedures has led a number of microsurgeons to attempt using a vascularized bone grafts to provide the affected bone with new vasculature and supportive strut graft augmented with spongiosa. The aim of the procedure is to curette necrotic bone at the subchondral area and substitute it with newly formed callus between the host bone and the transferred graft.

The core of the femoral head is exposed through an extracapsular approach from the lateral aspect of the greater trochanter. A tunnel is created through the femoral neck leading into the osteonecrotic lesion. After curettage of avascular bone the cavity is lined with cancellous autograft and the Free Vascularized fibula graft is inserted in the tunnel. The blood supply is reestablished with anastomosis of the peroneal vessels to the ascending branch of the lateral femoral circumflex artery and one concomitant vein.

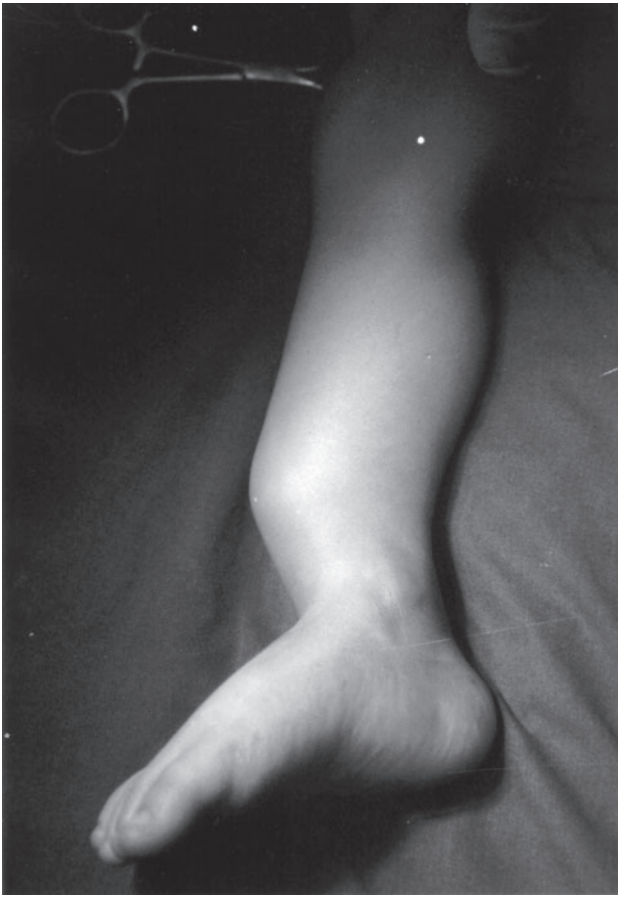


Fig. 10A.4. Congenital pseudarthrosis of the tibia in a 2 year old boy, managed with a free vascularized fibula. Adaptive hypertrophy in five months postoperatively allows complete functional recovery without support in five months.

The patient is kept on crutches and partial weight bearing for a period of three to four months until callus formation between the fibular tip, the surrounding spongiosa and the host bone.

This technique has been popularized by J. R. Urbaniak, MD in the USA who was among the first who started its application 1979, mastered the procedure and performed extensive laboratory and clinical research with vast clinical experience on more than 1500 cases. The long term follow up has demonstrated preservation of the hip joint in 85% of the cases operated prior to articular surface collapse. In patients operated after the establishment of collapse in the articular surface the procedure can delay the need for an arthroplasty up to seven years in 70% of the patients.

Fig. 10A.4, continued. Congenital pseudarthrosis of the tibia in a 2 year old boy, managed with a free vascularized fibula. Adaptive hypertrophy in five months postoperatively allows complete functional recovery without support in five months.

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Reconstruction of Large Skeletal Defects of the Extremities with:

B. The Iliac Crest Bone Graft

K. N. Malizos, Ch.G. Zalavras, Zoe Dailiana, A. Beris

Introduction

The vascularized iliac crest graft (VICG), although surpassed in popularity by the free vascularized fibular graft, remains a useful constituent of the orthopedic surgeon's armamentarium for the management of large bone defects and femoral head osteonecrosis.

The transfer of a VICG as a free flap was first reported in 1978 by Taylor, who utilized it as a composite flap for management of a lower extremity bone and soft tissue defect. Since then, it has been successfully employed in long bone, mandible and femoral head reconstruction.

Graft Properties

Anatomy

The VICG, harvested from the anterior part of the iliac crest and raised on the vascular pedicle of the deep or superficial circumflex iliac vessels, constitutes a corticocancellous bone graft that may reach a length of up to 10 cm.

The configuration of the VICG is distinct. It is broad and thin and has a curved shape, being convex when externally viewed. This may pose a limitation for diaphyseal reconstruction of long bones, but is an advantage when the metaphysis, the arch of the foot, the pelvis or the mandible is considered. The increased cross-sectional area facilitates reconstruction of metaphyseal bone defects and arthrodeses of joints.

The composition of the graft is mostly cancellous. Thus, ingrowth of blood vessels and osteoprogenitor cells over an increased graft surface is facilitated and healing is promoted. However, the inherent strength of the graft is limited and stable osteosynthesis may be difficult to accomplish.

The vascularity of the VICG is derived from two sources, the deep and the superficial circumflex iliac vessels. The deep circumflex iliac artery is considered to be more important. It originates from the external iliac artery and ascends along the inner surface of the anterior iliac bone or within the iliac muscle, providing many direct perforating branches to the iliac crest. The diameter of the artery is 1.5-3 mm and the pedicle may reach a length of 8 cm. The large diameter and the constant anatomy of the deep circumflex iliac artery compensate for the tedious approach.

The superficial circumflex iliac artery stems from the femoral artery and, in addition to the skin over the anterior iliac crest, it supplies the underlying bone via

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fasciocutaneous perforating branches. However, there are no branches directly supplying the bone and the offered vascularity may be precarious. Moreover, the diameter and length of the pedicle are smaller compared to the deep circumflex iliac vessels. The advantage of the superficial circumflex iliac pedicle, in addition to the easier dissection, is that it provides more consistent vascularity to the skin component.

Biology

The VICG maintains its viability and thus shares all the advantages of vascularized bone grafts over avascular ones, which include enhanced healing and hypertrophy, biomechanical superiority and provision of vascularity at the recipient site.

Versatility

The VICG derives its versatility from the characteristics of its vascular supply. Since the main source of vascularity is not a single endosteal vessel, but multiple perforating branches from 2 separate pedicles, the graft can undergo osteotomies to conform to the defect and still maintain its vascularity.

Both the deep and superficial vascular pedicles provide vascularity to the overlying skin, therefore allowing the simultaneous harvesting of a large skin paddle measuring up to 10 x 30 cm. Reconstruction of composite defects can thus be achieved by an osteocutaneous flap.

However, blood supply to the skin paddle is dependent on musculocutaneous perforators that can be twisted and occluded if the skin component is transposed relatively to the bone. Thus, the normal relationship of the skin component to the bone graft should be maintained.

Moreover, harvesting of an osteomuscular flap is possible by including part of the internal oblique muscle attached to the bone. Even an osteomusculocutaneous flap has been described based on both the deep and superficial iliac pedicles. Thus, the VICG can be raised as a double-pedicle flap to ensure viability of the soft tissue component when placement of the flap will result in alteration of the skin-bone relationship. Epiphysis transfer is not feasible, in contrast to the vascularized fibular graft.

The VICG can be harvested in a “split” fashion, consisting only of the inner table of the ilium, to provide a less bulky graft.

The VICG can be transferred not only as a free flap necessitating microvascular anastomoses, but also as a pedicled flap to the proximal femur, due to the increased pedicle length and the proximity to the hip region.

General Treatment Considerations

Indications

The VICG can address pathologic conditions where conventional avascular grafts or other simpler procedures would not be suitable. The two main indications are skeletal defects (greater than 5 cm but less than 10 cm, accompanied by a poor soft tissue envelope or located in the proximal femur) and femoral head osteonecrosis.

Preoperative Planning

Meticulous evaluation of defect, soft tissue, limb and patient factors, as outlined in the respective section of Chapter 10A (free vascularized fibular graft), is mandatory.

Assessment of the donor site should include determination of the maximum dimensions of the graft and of the skin paddle and selection of the left or right donor site. Bone models with detachable iliac crests may be particularly helpful in planning. Since the pedicle enters the anterior concave part of the graft, the different location of the vessels in the left or right graft may make one side preferable to the other in relation to the defect characteristics and the location of the recipient site vessels. In reconstruction of the tibia the ipsilateral iliac crest is preferable if the anterior tibial will be the recipient artery, whereas the contralateral iliac crest should be harvested if the posterior tibial artery will be utilized. In lower extremity defects, the ipsilateral iliac crest has the advantage of being less painful postoperatively, due to avoidance of weight bearing on that side. Previous trauma or bone harvesting from one of the iliac regions will preclude its use.

In composite defects, the location and relationship of the bone and the soft tissue defect should be evaluated to determine optimal placement of the graft and ascertain that the skin component will not be transposed. If this is not the case, alternative flap designs should be employed. For soft tissue defects less than 6 x 14 cm an osteomuscular flap can be utilized and for larger defects inclusion of the superficial circumflex iliac pedicle is advocated.

Moreover, choice of the vascular pedicle and the respective approach should be made. The deep circumflex iliac vessels are preferable, except when a pedicled groin flap with only a small bone graft is desirable, as in cases of osteoplastic thumb reconstruction. Angiography may be useful for detection of anatomic variations.

Surgical Technique

The simultaneous preparation of the donor and recipient sites by two operative teams will considerably decrease operative time.

Graft Harvesting

Deep Circumflex Iliac Pedicle

The VICG is harvested with the patient supine. The incision extends from the inguinal ligament to the anterior iliac crest and, if needed, incorporates a skin paddle centered on the longitudinal axis of the iliac crest. The inguinal canal is exposed and the deep circumflex iliac artery is dissected beginning at its origin from the external iliac artery and proceeding proximally. It ascends along the inner surface of the anterior ilium or within the iliac muscle, being 2 cm caudal to the iliac crest. Care should be taken to avoid severing the iliac muscle and fascia along the course of the vessels, but incise them at the same level as the osteotomy so as to incorporate the intact vessels. The soft tissue component should be elevated with caution to avoid any interference with its connections to the fascia overlying the external oblique muscle and the iliac crest. Musculotendinous attachments are reflected from the iliac crest. Osteotomy follows, the graft is observed for bleeding and the pedicle is divided. Wound closure should be carefully executed to avoid postoperative hernias.

Superficial Circumflex Iliac Pedicle

The surgical technique is ideal to groin flap elevation with the additional inclusion of an iliac crest bone graft. Dissection is considerably easier and the inguinal canal is spared.

Two Pedicles

Dissection of the superficial in addition to the deep pedicle has been proposed by some authors as a means of increasing the reliability of the skin component of the composite VICG.

Recipient Site Preparation and Defect Reconstruction

Guidelines for preparation of the recipient site and reconstruction of the defect have already been discussed in Chapter 10A (free vascularized fibular graft). When a VICG is used, however, the surgeon should be familiar with the potential for graft configuration and aware of the limitations in graft fixation.

The VICG can undergo one or more osteotomies without any compromise in graft vascularity, due to the presence of multiple arterial branches supplying the bone. Therefore, it can be shaped appropriately in order to optimally reconstruct the existing defect. Taylor advocated a wedge osteotomy to straighten grafts longer than 8 cm and prevent stress fractures.

Screw purchase into the cancellous bone of the iliac crest is limited. Thus, internal fixation by plate and screws will not provide adequate stability. External fixation is preferable and can be supplemented by an additional Kirschner wire or screw.

Postoperative Follow-up

In the immediate postoperative period bed rest is advised for 3-5 days until pain subsides. Flexion of the hip will protect the donor site repair from excessive tension.

Postoperative follow-up will follow the guidelines for vascularized bone grafts (Chapter 10A)

10B

Complications

Specific donor site complications associated with VICG harvesting include incisional hernia (7% in the series by Han et al) and inguinal hernia due to the approach through the inguinal canal.

Partial loss of the skin component has been reported.

Specific Treatment Considerations

Bone Defects

The free VICG has been successfully utilized as a free flap for the management of osseous and composite defects of the extremities and the mandible.

Bishop collectively evaluated the published experience with this flap and reported a time to union of 7 months and a time of protected weight bearing of 18 months. Eventual union occurred in 67% of cases, with 38% requiring secondary bone grafting.

A tendency for necrosis of the skin paddle was observed.

Han et al reported an overall union rate of 89% with primary union in 57%. In this series the selection of donor site, i.e., the VICG vs. the vascularized fibular graft, was not associated with a statistically significant difference in union rates, either primarily or following bone grafting.

David et al successfully reconstructed 91% of mandibular defects utilizing the free VICG as an osseous or a composite flap.

The VICG can also be employed as a pedicled flap for reconstruction of proximal femoral defects.

Femoral Head Osteonecrosis

The VICG has found application as a pedicled flap in the management of femoral head osteonecrosis. The graft is prepared on the deep circumflex iliac artery pedicle and then it is tunneled beneath the iliac muscle to reach the ipsilateral hip. The femoral head is exposed, following external rotation of the hip and division of the capsule, and a tunnel is created in the femoral neck leading into the osteonecrotic head. Avascular bone is removed, the femoral head is packed with cancellous autograft and the VICG is inserted in the tunnel maintaining its vascularity.

The pedicled VICG does not require microvascular anastomoses, therefore the procedure becomes technically easier and viability of the graft more probable when compared to the free vascularized fibular graft. However, with the VICG the joint capsule is violated and the structural support provided is inferior. Leung reported good results in early stages of the disease after a 4-12 year follow-up, but the experience with this technique is limited.

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Reconstruction of Large Skeletal Defects of the Extremities with:

C. Free Vascularized Fibula Graft Plus Bone Allograft after Intercalary Resection in Malignant Bone Tumor

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Introduction

During the last two decades bone allografts have been widely used in the treatment of large bone defects after resection of bone tumors. Several complications have been associated with the use of this reconstructive technique. In a study carried out in 1992, Mankin et al[1] reported the occurrence of fracture in19% of those who had undergone the procedure, 14% nonunion, 10% infection.

In 1995 Aranguren et al evaluated host-allograft fusion: they studied 83 cases involving allograft. They found that the average time necessary for bone fusion was 6.5 months for metaphyseal junction and 16 months for diaphysis.[2] The postsurgical period which lasts about 2-3 years is primarily characterized by allograft bone resorption:mechanical strength decrease progressively. Berrey et al[3] and Zehr et al[4] reported that a high incidence of allograft fractures occurs two years after surgery. Furthermore, the use of allograft requires a long period of immobilization, with a great discomfort for the patient.

The use of vascularized bone graft (VFG)is an alternative in the treatment of long bone defects. Although rapid bone union can be achieved even in the presence of a scarred or irradiated bed, some complications have been reported. Stress fractures are frequently observed and they usually occur during the first postoperative year, when the vascularized bone graft is still weak and not able to take full weight bearing.[5]

The rationale of a combined graft (VFG+allograft)[6,7] is to associate the advantages provided by the mechanical endurance of a massive allograft to the biological properties of the vascularized fibula graft. The allograft provides adequate bone stock and early stability, while the VFG facilitates the host-allograft union, and has the ability to heal and leads to hypertrophy.

Materials and Methods

A retrospective study was carried out on 52 patients who had been operated between 1988 and 1998. All subjects had undergone a combined graft (allograft + free

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vascularized fibula graft) for reconstruction of bone loss after resection of a diaphyseal or metadiaphyseal bone tumor. The mean age of patients was 16.5 years range from 4-48. The two most frequently diagnosed tumors were osteosarcoma (28 cases) followed by Ewing's sarcoma (10 cases). The others were affected by various bone tumors (Table 10C.1). The tibia was reconstructed in 38 patients, the femur in 12, and the humerus in 2. The mean length of the resection was 15.8 cm (range 9-26 cm); the mean length of vascularized fibula graft was 19.6 cm (range: 12-28 cm).

Tibial reconstruction was performed with a VFG concentrically placed into the allograft in 35 patients and in parallel dual assembling in 3 cases. Femoral reconstruction with one VFG concentrically placed into the allograft in two cases and dual assembled in the others. The two cases of humeral defects were reconstructed with a VFG plus allograft in concentric assembling.

Mean follow-up was 46 months range 3.5-114 months.

The Surgical Technique

Surgery is performed simultaneously by two teams. While the tumor team performs the resection, the microsurgical team harvests the controlateral fibula. Usually, the VFT must exceed the length of the oncologic resection by approximately five centimeters. Microsurgeons and tumor surgeons worked in collaboration during resection. The microsurgeon isolates and protects the recipient vessels.

In combined bone graft procedures the VFG can be used in concentric assembling or in parallel dual assembling, with the allograft.

The concentric technique is recommended for tibia reconstruction[6] where soft tissue closure is difficult. In the event of a skin defect, an osteocutaneous flap may be planned: otherwise, a local muscular flap may be rotated to cover the implant. In our experience only in one case of large soft tissue defects, a free latissimus dorsi flap was prepared.

An oversized allograft should be used given that a wide medullary canal can contain the fibula. The anterior cortex is opened and the medullary canal is reamed until the fibula fits into it (Fig. 10C.1). Great care must be taken to avoid damage to the vascular pedicle during the insertion of the fibula into the allograft shell. The positions of the vascular pedicle of the VFT and that of the recipient vessels must be evaluated before osteosynthesis. Any traction, change in angulation, twisting or pressure on the pedicle must be avoided. A groove can be carved into the allograft to obtain a "safe" position for the vascular pedicle, thus avoiding any impingement on any sharp margin. The microsurgical team must cooperate with the tumor team during preoperative planning. All the variables that can interfere with the microvascular outcome, must be taken into consideration.

In cases of intraepiphyseal resection, where just a thin part of the epiphysis and the articular surface are saved, the use of concentric assembling allows for minimal juxta-articular osteosynthesis with the use of multiple screws. When the growth plate is preserved, bone fixation is performed by passing Kirschner wires through the epiphysis in order to prevent ephiphysiodesis. At the other end of the combined graft, fixation is usually achieved using plate and screws. If sufficient bone is spared at both ends of the resection, rigid fixation is carried out using a long plate, which crosses both osteotomies.

Table 10C.1. Histological diagnosis of treated patients

Diagnosis	N° of Cases
Osteosarcoma	28
Ewing's Sarcoma	10
Adamantinoma	4
Fibrosarcoma	3
Malignant Fibrous Histiocitoma	3
Dedifferentiated Chondrosarcoma	1
Angiosarcoma	1
Desmoplastic Fibroma	1
Giant Cell Tumor	1
TOTAL	**52**

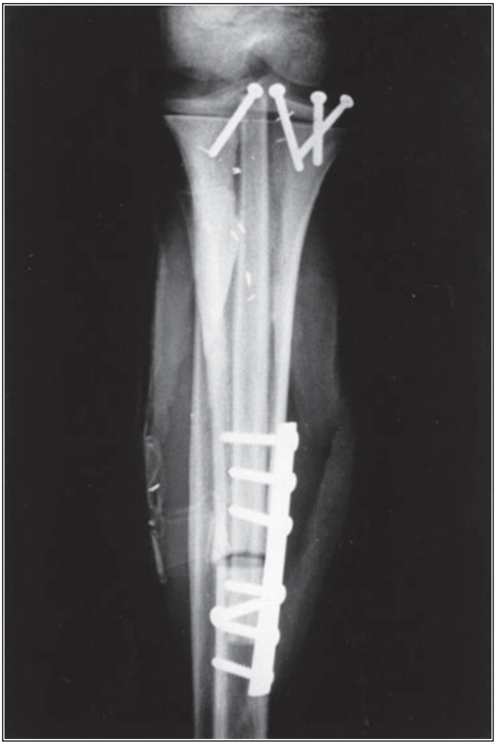

Fig. 10C.1. Example of combined bone graft procedure. The VFG is used in concentric assembling for tibia reconstruction.

Parallel dual assembling is widely used in diaphyseal reconstruction of the femur (Fig. 10C.2). In such cases the allograft is used for intercalary reconstruction and fixation is carried out using long plate which bridges the osteotomy sites: VFG is

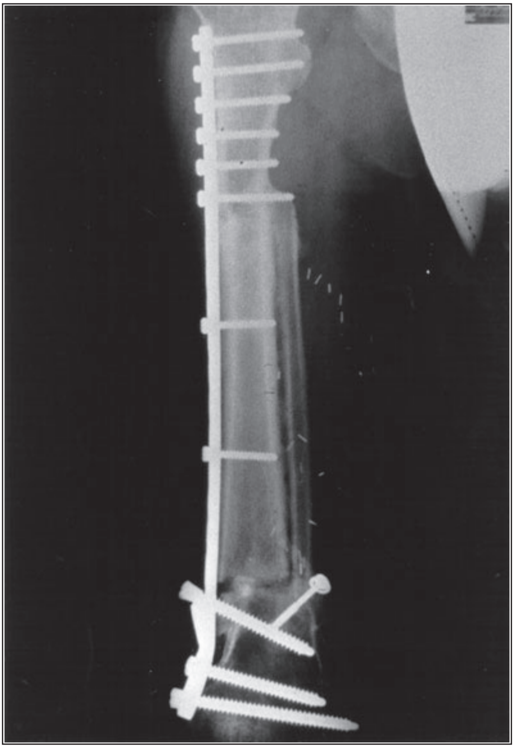

Fig. 10C.2. Example of parallel dual assembling in diaphyseal reconstruction of femur.

fixated medially to the allograft. Extremities are placed in or are in contact with the femoral bone. This procedure can reinforce the medial cortex and permit the vascular anastomosis with branches of the deep femoral artery, which lies medially.

When the resection must be performed very close to the growth plate or to the articular surface, concentric assembling, with minimal osteosynthesis, is preferred even in the femur.

Normally in the case of tumoral resection, vascular pedicles can be found rather easily at the side of anastomosis. A termino-terminal anastomosis with the anterior tibial vessels in direct or reverse flow, was the most often used type of vascular reconstruction in the leg, in our series. Using an upside down fibula, a termino-lateral anastomosis with posterior tibial artery was sometimes but rarely performed.

After surgery, the patient is immobilized in a cast for four to six weeks. When the cast is removed, the proximal and distal joints are mobilized for a few days. A new cast is than applied for an additional period of time of at least four weeks. Afterwards, a brace must be worn until union is achieved. Once union has been achieved, progressive weight bearing is allowed.

Clinical Outcome

The mean time of consolidation of free VFG at the junction site was 2.7 months. The mean time for the allograft at the same level, was 8 months. Full weight bearing was allowed after a mean time of 13.7 months age (3.5-24 mos.). A fracture of the implant occurred in 11 out of the 52 cases (21%). Eight patients had undisplaced stress fractures and three were fractures involving both the allograft and VFT. In ten cases, the fractures underwent spontaneous healing with hypertrophic callous of the VFG after cast immobilization. One patient required autologous bone grafting for healing. No major revision procedures were required.

In two cases of tibia reconstruction nonunions at osteotomy site were noted; complete union was then achieved after autologous bone grafting and recasting.

Three cases of local recurrence were found. In two other cases, one angiosarcoma and one dedifferentiated chondrosarcoma developed a distal skip metastasis in the same bone. Three patients developed pulmonary metastasis and two of them died of the disease. One patient is disease free after metastasectomy. Postoperative wound slough was noted in two cases of tibia reconstruction, both of them healed after surgical debridement. One patient had developed a deep infection which required amputation of the tibia.

Discussion

The use of the combined graft procedure is based on observations of the intrinsic properties of the allograft and of the vascularized fibula graft. By combining the two, the advantages of each technique can be fused into a single procedure. In fact there are no limits to the size of the allograft, which allows for stable bone fixation. However, progressive resorption, the long period of time necessary for fusion and the high rate of nonunion[8,3,4] are among the limits when only this procedure is used. The addition of vascularized fibula graft can eliminate these disadvantages. The live bone heals quickly, hypertrophy occurs progressively and maintains the allograft when it is weakened by biological phenomena (Fig. 10C.3). In addiction the VFG seems to be able to induce osteointegration of the allograft and facilitates bone union at the level of osteotomy at a significantly shorter period of time. These clinical observations require further experimental study to better understand the reasons for these phenomena and to confirm the benefits.

This technique has both optional and absolute indications. Intercalary resection is an optional indication. When combined graft is carried out recovery time and the incidence of complication are reduced. Absolute indications are defined as those which involve metaepiphyseal resections, growth plate salvaging and arthrodesis of the ankle.

Metadiaphyseal tumors of the knee joint are commonly treated by intra-articular resection even when the articular surface and the subchondral bone are not involved in the tumoral processes. In these cases, an intraepiphyseal resection can be performed. A thin fragment of articular surface should be preserved, and intercalary reconstruction is feasible with the combined allograft procedure. Minimal fixation is necessary at the epiphyseal osteotomy, while rigid osteosynthesis is required at the diaphyseal level. The union at the junction sites is achieved into the first 3-4 months. Initial stability of the implant is provided by the allograft, and later stability is supplied by the hypertrophied fibula.

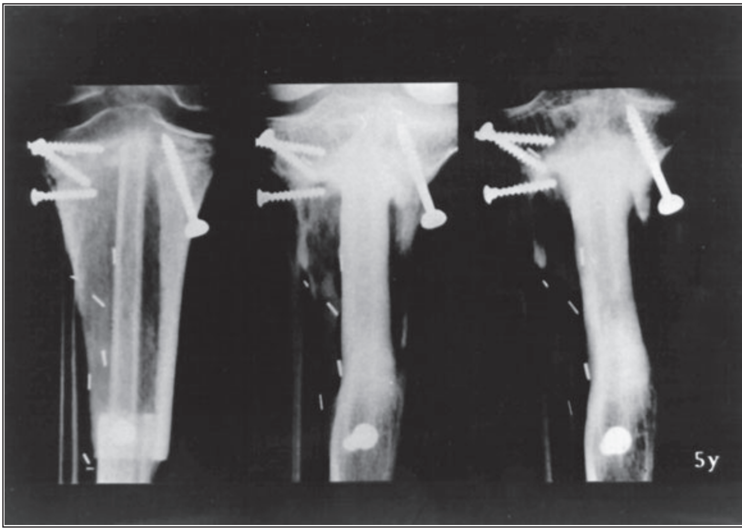

Fig. 10C.3. Reconstruction of the tibia. Hypertrophy of the VFG progressively occurs while the allograft is resorpted.

In growing patients, if the metadiaphyseal tumor does not involve the growth plate and resection can be performed preserving the epiphysis, combined allograft reconstruction with minimal fixation of the graft (Kirschner wires or screws) can avoid epiphysiodesis (Fig. 10C.4). Our experience has shown that, in spite of the relatively less rigid fixation, the vascularized fibula provides the necessary biological activity to enhance bone union and a rapid recovery of the patient.

When distal tibial resection is performed, arthrodesis reconstruction with combined allograft procedure, is feasible. With minimal screw fixation of the grafts arthrodesis can be achieved with the talus preserving the subtalar joints (Fig. 10C.5). In this situation, especially in children, subtalar joint function permits a flexion-extension range of up to 60°.

In conclusion the procedure with hybrid combined bone graft (VFG+allograft) is an innovative technique. The advantages of mechanical resistance by a massive allograft are associated with the biological properties of the vascularized bone graft. With this technique an early recovery of the patient and a progressively increasing strength of the reconstructed bone are obtained. Combined bone grafts represent an elective reconstructive option in such particular situations as juxta articular resections, juxta epiphyseal resections in growing patients and resections of distal tibia requiring ankle arthrodesis.

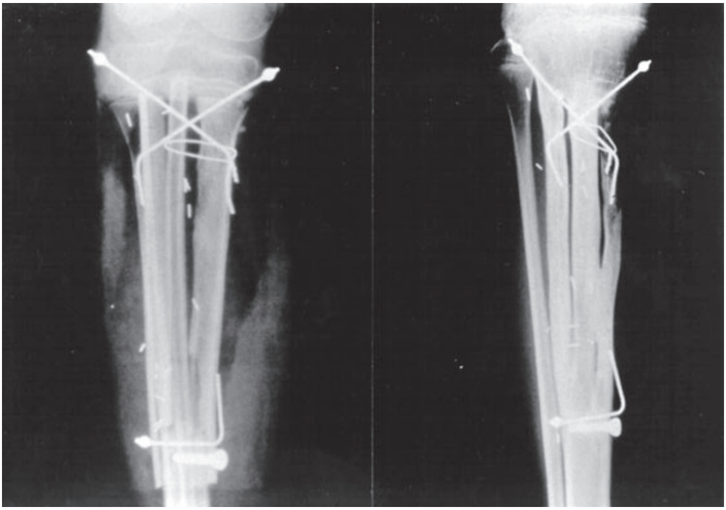

Fig. 10C.4. Tibial reconstruction after metadiaphiseal resection, performed sparing the epiphysis. In growing patients combined graft with minimal bone fixation can avoid epiphysiodesis.

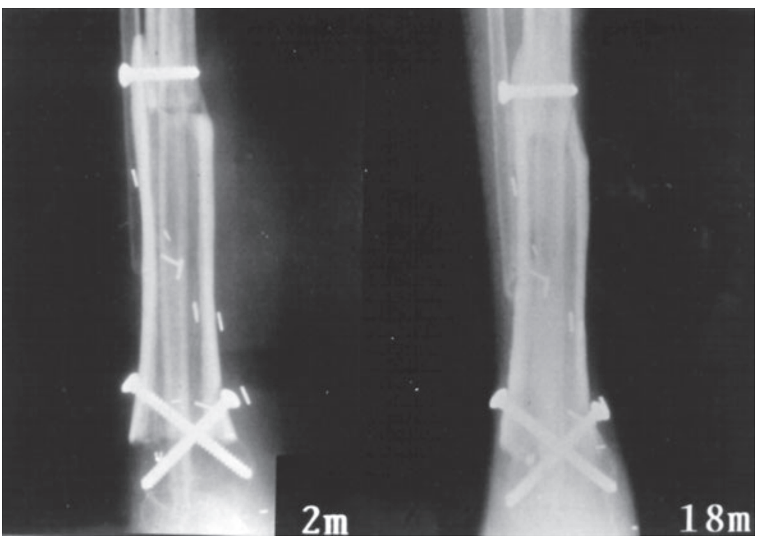

Fig. 10C.5. Distal tibia reconstruction. Arthrodesis performed with the talus. The minimal screws fixation of the grafts preserves the subtalar joint.

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CHAPTER 10

Reconstruction of Large Skeletal Defects of the Extremities with:

D. Clinical Application of Growing Bone Transfer

Marco Innocenti, Massimo Ceruso, Luca Delcroix, Marco Manfrini, Rodolfo Capanna

Introduction

The advantages of vascularized bone transfer versus conventional nonvascularized autograft are well known. The ability to heal according to physiological rules, the possibility to reconstruct long bone defects even in scarred or infected beds, the bone remodeling and hypertrophy under the influence of loading are some of the most remarkable features of vascularized autografts. In skeletally immature patients, the harvest of vascularized epiphysis along with a variable amount of adjoining diaphysis may provide the potential for growth of the graft. Such a procedure results to be highly valuable when an active growth plate, included in oncological resection or involved in destruction for traumatic or infective reasons, has to be biologically reconstructed. The aim of the procedure is the reconstruction of bone loss and simultaneous restoration of growth potential preventing future limb discrepancy.

Autologous epiphiseal plate transfer have been pioneered by several surgeons since the beginning of this century.[1-3] The reported results referring to premicrosurgical era are disappointing in the majority of cases and the sporadic successful cases are probably related to the small dimension of the transferred physes and subsequent possible neovascularization from the adjoining recipient bone. The experimental investigations carried out by several authors in the past 30 years[4-13] seem to agree that the feasibility of the technique depends on adequate blood supply both to the growth plate and to the diaphysis ; thus a failure in revascularization leads to premature fusion of the growth plate and possible nonunion with the host bone.

In the eighties, the vascularized epiphyseal transfer left its experimental dimension to enter the clinical scenario.[14-17] The developing of reliable microsurgical technique allowed to apply in the clinical practice the vascularized transfer improving the success rate of such a procedure.

Three donor sites have been suggested in order to reconstruct epiphyseal defects in children: the iliac crest, the inferior portion of the scapula and the proximal fibular epiphysis. All the above mentioned segments can be harvested with minimal morbidity in the donor area and all them contain active growth plates. However, the iliac crest and the scapula can be anatomically classified as apophysis and they do

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Fig. 10D.1. A preoperative arteriography is routinely performed in order to detect the recurrent epiphyseal branch of the anterior tibial artery (arrow). The epiphyseal vessel raises from the anterior tibial artery approximately 2 cm after its emergence in the anterior compartment of the leg.

not have the features of a true epiphysis.[18] In particular, they fail in providing a true articular surface with unpredictable functional outcome after the transfer. By contrast, the proximal fibular epiphysis satisfies all the biological and biomechanical requirements in case of replacement of the epiphyseal portion of a long bone and for this reason the proximal fibula became the most popular graft in order to reconstruct the distal radius and the proximal humerus in the pediatric age.

The blood supply of the fibula has been extensively studied.[19,20] The anterior tibial artery provides a constant recurrent branch to the proximal fibular physis (Fig. 10D.1) and therefore it may be used as the vascular pedicle for a distant transfer of such a graft. The peroneal artery (with or without the lateral inferior genicular artery) has also been used as the vascular pedicle for such physeal transfers, but with inconsistent results. Taylor's anatomical investigations[21] confirmed the role of the anterior tibial artery in the vascularity of the fibular growth plate and also demonstrated that sufficient blood supply can be provided to the proximal diaphysis by small musculo periosteal branches raising from the same artery. Thus, the anterior tibial artery is able to supply the graft, provided that both the epiphyseal vessel and the diaphyseal periosteal vascular network are preserved during the dissection.

Operative Technique

Harvest of the Fibula

The lateral approach described by Gilbert is not applicable in case of fibula transfer based on the anterior tibial vascular system because it neither permits a safe dissection of the vascular bundle nor a sufficient view on the proximal tibio-fibular joint.

An antero-lateral approach, thorough the intermuscular plane between tibialis anterior and extensor digitorum longus muscles, allows complete visualization of the delicate periosteal and juxtaphyseal vascular networks on which this transfer is based (Fig. 10D.2). The dissection proceeds from distal to proximal and great care must be taken in saving as many periosteal branches as possible. This goal is better achieved if the interosseous membrane is sharply detached from the tibia so that the vascular pedicle and its branches lie undisturbed on their natural bed.

The peroneal nerve must be dissociated from the anterior tibial vessels. The nerve surrounds the vascular bundle according to an intricate three-dimensional pattern and the dissection is therefore very tedious and time consuming. In some instances it is necessary to divide some of the motor branches to the anterior compartment muscles to free up the vascular pedicle; in that case a neurorraphy or a direct neurotization should be performed.

In order to expand the view on the proximal surgical field, the extensor digitorum longus and the peroneus longus muscles must be divided from their insertion on the proximal fibula and tibia. This allows a better visualization of the upper part of the pedicle and of the tibio-fibular joint. Finally, all the muscles inserted along the desired amount of fibular shaft are detached from the bone, carefully preserving an adequate muscular cuff around the periosteum. 10D

To facilitate soft tissue reconstruction around the fibular head, a part of the biceps femoris tendon is split and harvested with the fibula. After osteotomy at the appropriate distal site and dislocation of the proximal tibio-fibular joint, the fibula is left attached to its vascular pedicle and the tourniquet released. Bleeding should be observed either from the muscular cuff surrounding the physis or from the medullary canal. Then, the pedicle is divided and the fibula is transferred to the recipient site.

Great care must be taken in repairing the lateral structures which stabilize the knee joint. The lateral collateral ligament, enhanced by the residual strip of biceps femoris tendon, is fixed to the lateral aspect of the tibia by means of transosseous stitches and stability is checked.

Reconstruction of the Distal Radius

The anterior surgical approach described by Henry is preferably adopted in order to expose the distal radius. In case of tumor resection a variable amount of soft tissue should be included in the resection according to the preoperative planning. The saLVAge of the ulna greatly concurs to improve the final functional outcome.

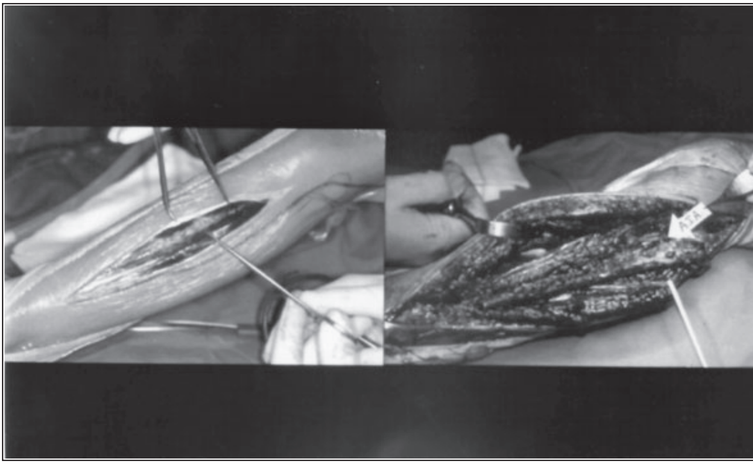

Fig. 10D.2. An anterolateral approach is recommended in order to expose the anterior tibial neurovascular bundle. The dissection is carried out in the intermuscular space between tibialis anterior and extensor digitorum longus muscles. The latter, and the peroneus longus are then sharply detached from their proximal insertion in order to dissect the upper part of the pedicle and the fibular epiphysis. An adequate muscular cuff must be preserved around the epiphysis to reduce the risk of damaging the small epiphyseal artery which supplies the growth plate (arrow).

Due to anatomical similarities, the contralateral fibula is usually preferred in the reconstruction of the distal radius. The bone fixation can be achieved either by plates or lag screws and it is usually facilitated by correspondence in transverse diameter between donor and recipient bones. The wrist joint is temporarily stabilized by a Kirshner wire which will be removed one month after surgery. The strip of biceps femoris tendon is used for soft tissue repair and anchored to the remaining distal radiocarpal capsule. By contrast, the distal radioulnar joint is left lax in order to prevent impingement between fibula and ulna which might interfere with pronosupination.

A reverse flow arterial end to end anastomosis is then performed with the recipient vessel which may be either the radial artery or the common interosseous artery. The selected recipient vein is usually the cephalic vein. At the end of vascular repair bleeding should be observed from both the muscular cuff surrounding the epiphysis and the diaphysis. An above elbow cast is applied during the first month postoperatively.

Reconstruction of the Proximal Humerus

In spite of the obvious dimensional discrepancy between the epiphyses of the humerus and the fibula, the described procedure is indicated also in the reconstruction of the proximal humerus and provides good functional results.

In this anatomical district the osteosynthesis is accomplished by plates. In order to improve the elasticity of the implant and to prevent possible fractures, which in

Fig. 10D.3. In humeral reconstruction, the bone fixation is achieved by means of long reconstruction plates. The distal fibula is inserted into the medullary canal of the humerus. In order to improve the elasticity of the implant and to minimize the damage to the fibula, few 2,7 screws should be used to fix the plate to the transferred bone.

our early cases occurred at the level of the most proximal screw, it is recommended the use of long reconstruction plates which should be fixed by few screws (Fig. 10D.3). The resulting implant is much less rigid than that achievable with a traditional compression plate and the distribution of the mechanical stresses is more homogeneous. When possible, an intramedullary insertion of the fibula in the distal stump of the humerus is highly recommended. In that case, an oversize distal periosteal cuff should be preserved in the fibula and used to overlap the osteotomy site in order to facilitate the bone fusion.

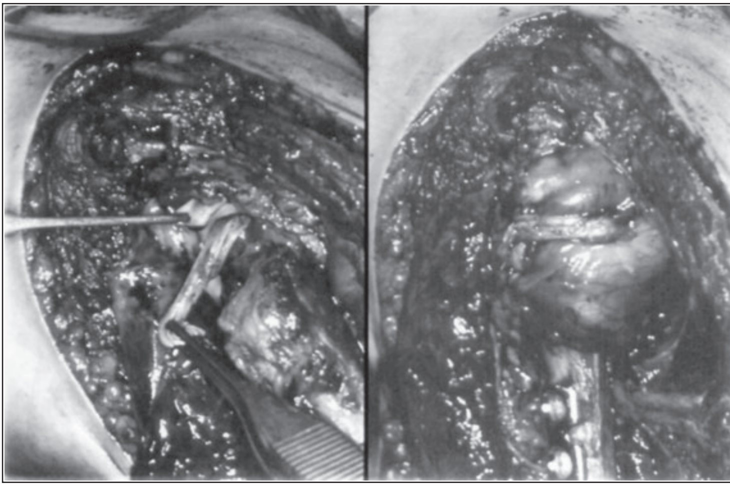

Fig. 10D.4. The stability of the shoulder depends on appropriate soft tissue reconstruction. Note the strip of biceps femoris tendon which is usually anchored to the glenoid in order to improve the stability of the joint. The rotator cuff is sutured contouring the fibular epiphysis.

The soft tissue repair around the transferred epiphysis is complicated by the potential danger for the epiphyseal vascular network related to direct reinsertion on the bone of the rotator cuff and deltoid. For this reason the muscles are just sutured around the fibular head and the strip of biceps femoris tendon is anchored to the glenoid achieving acceptable stability (Fig. 10D.4). In some cases, however, a proximal displacement of the physis does occur due to anatomical discrepancy and insufficient stabilization.

In humeral reconstruction the suggested recipient artery is the deep humeral artery. When it is not available or too small in diameter, an end to side anastomosis with the brachial artery is preferred.

Results and Discussion

Our personal experience with epiphyseal plate transplantation in upper limb skeletal reconstruction refers to a population of 20 patients ranging in age between 3 and 11 years.[22] All of them were affected by malignant bone sarcomas located in the meta-ephyphisis of a long bone of the upper extremity. The described reconstructive procedure was used to replace the proximal humerus in 15 cases and the distal radius in five. The follow up period ranges between nine months and eight years.

The analysis of the results should take into account such variables as graft survival and bone fusion, quality and quantity of growth, remodeling of the transplanted bone, functional outcome and morbidity at the level of donor site.

As far as the viability of the grafts and their fusion with the host bone is concerned, we observed a rapid bone union in all cases and the reliability of the diaphyseal blood supply was further on confirmed in those patients who were investigated

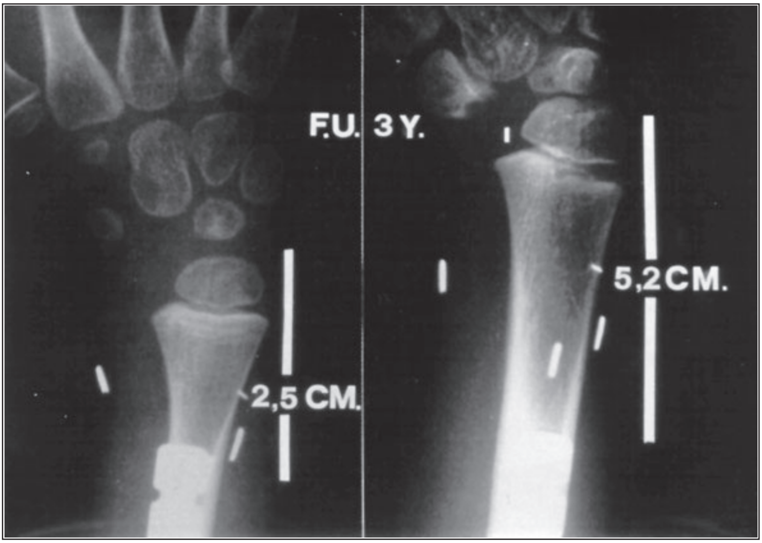

Fig. 10D.5. The distance lain between a fixed landmark (the plate) and the tip of the epiphysis is periodically evaluated in order to assess the axial growth of the transferred fibula.

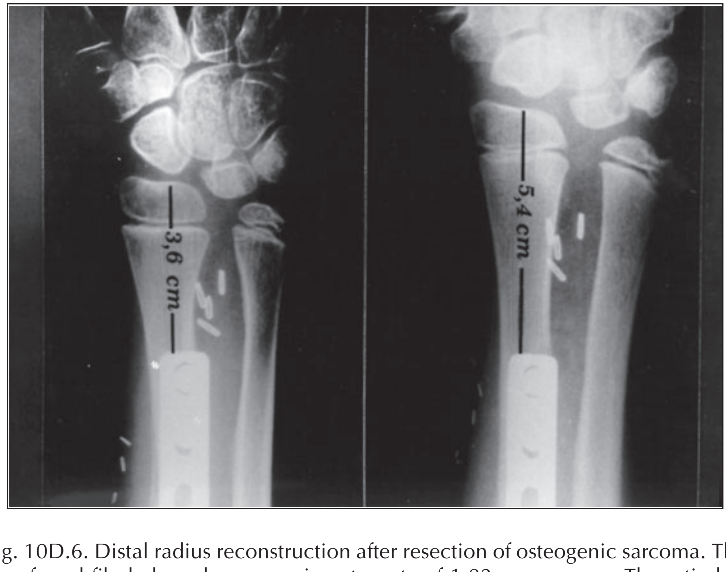

Fig. 10D.6. Distal radius reconstruction after resection of osteogenic sarcoma. The transferred fibula have been growing at a rate of 1.02 cm per year. The ratio between the fibular head and the caput ulnae remained unchanged thus indicating a symmetrical growth of the two bones.

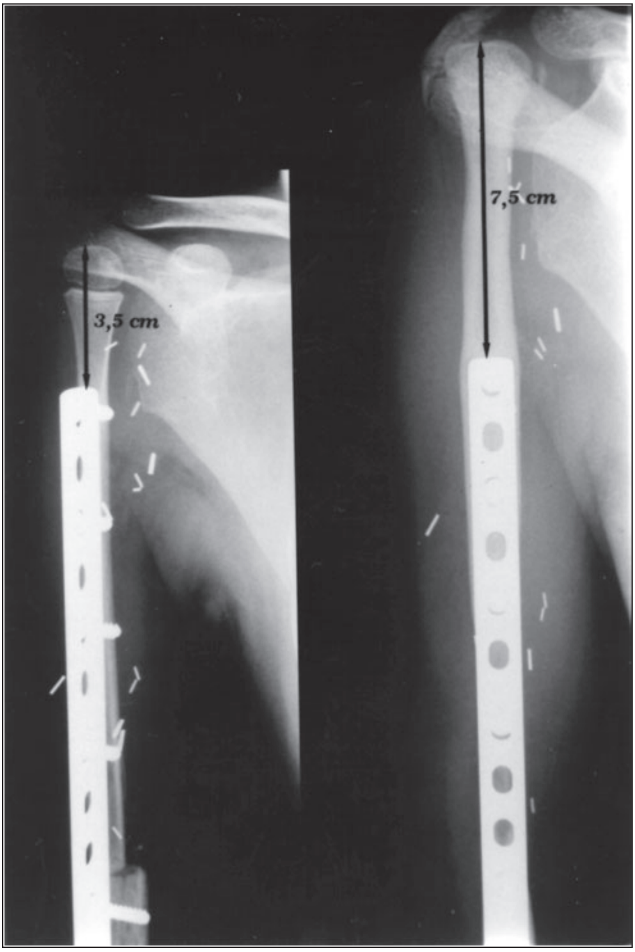

Fig. 10D.7. Reconstruction of the proximal two thirds of the humerus after resection of osteogenic sarcoma. The total growth after 62 months of follow up amounts to 4 cm with a growth rate/year of 0.77cm.

by means of postoperative bone scan. Thus, our experience seems to validate the hypothesis that the anterior tibial vascular network is able to supply the proximal two thirds of the shaft of the fibula and that there is no need to include the peroneal artery in the described surgical model.

The amount of growth of the transferred bone have been assessed evaluating the distance between a fixed point, usually the plate or a screw, and the tip of the epiphysis (Fig. 10D.5). The overall growth and the growth rate per year have been the parameters taken into account in all cases. In our population of neoplastic patients some inhibition of growth at any level, which is supposed to be related to the use of adjuvant chemotherapy,[23] should be considered as long as such a therapy is applied. The growth rate of controlled patients with a follow up period longer than 2 years ranges between 0.75 and 1.33 cm per year (Figs. 10D.6, 10D.7). In a current research, we are processing the data related to the growth trend of the grafts with the aim to identify those variables which are involved in determining the progressive lengthening of the bone. The age of the patient at surgery, the recipient site, the blood supply, and the approaching to skeletal maturity are some factors which seem to play some role in the amount of growth registered every year.

A failure in longitudinal growth and premature closure of the growth plate have been observed in 5 patients. In two cases the graft was supplied by the peroneal artery which is a controversial pedicle in order to vascularize the epiphysis. Our experience seems to confirm the opinion of those authors who state that the peroneal artery supplies only the shaft of the fibula and that the peroneal pedicle should be enhanced with an epiphyseal artery, usually the descending genicular artery, when the epiphysis is a component of the graft.[24]

The plastic properties of the epiphysis after its transfer in heterotopic location have been evaluated comparing radiographs and three-dimensional T.C. scans taken at different times. The remodeling observed in wrist reconstruction have been quite significant in most cases. Probably as a consequence of axial load, the fibular epiphysis is able to adapt its articular surface to the shape of the proximal carpal row developing a concave surface and progressively improving stability and range of motion. Such a remarkable finding has not been observed in case of proximal humerus

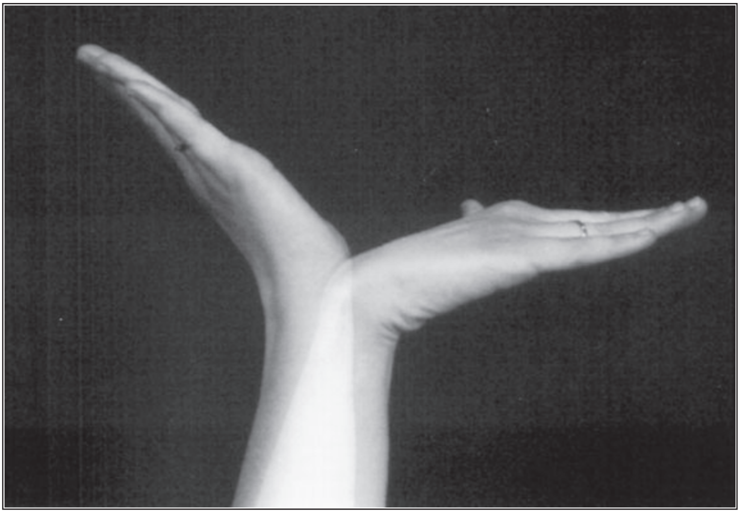

Fig. 10D.8. Wrist motion seven years after surgery. Excellent results can be achieved in distal radius reconstruction. A nearly normal range of motion on all planes have been recovered in all the cases.

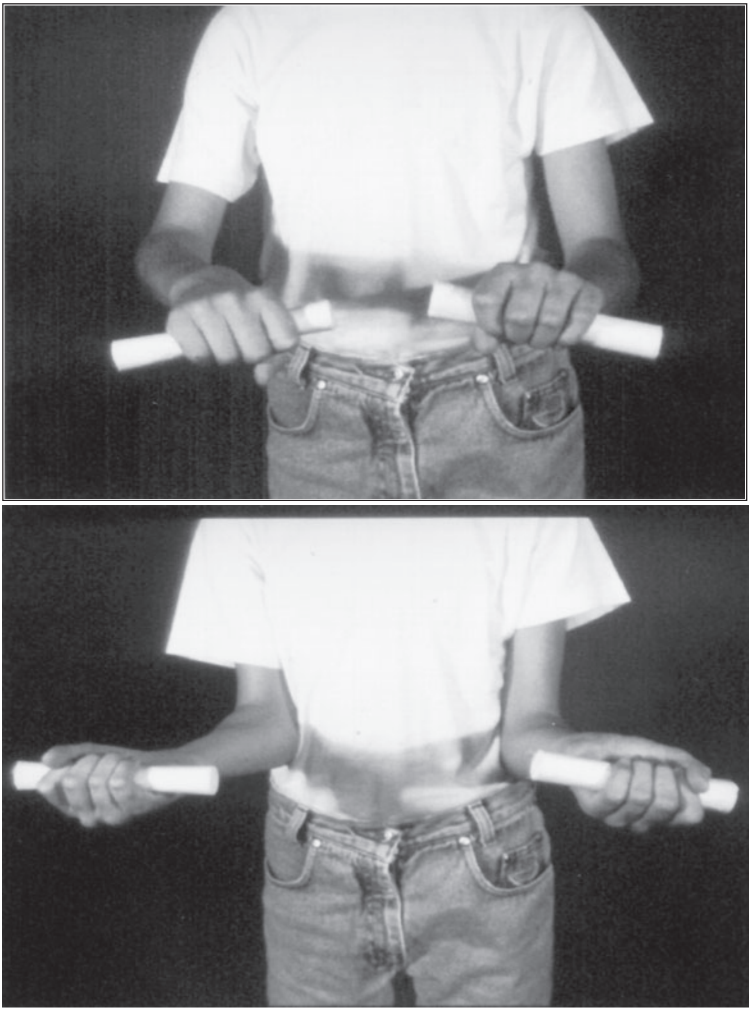

Fig. 10D.9. (A, B). In order to provide a satisfactory recovery of pronation and supination, it is suggested a pretty lax suture of the soft tissue which stabilize the distal radio-ulnar joint.

replacement, where the fibular head remains substantially unchanged even several years after surgery.

From a functional point of view, excellent results can be achieved in distal radius reconstruction (Fig. 10D.8). In all cases where the ulna could be spared during tumor resection, the range of motion was almost fully recovered after an adequate period of rehabilitation. Furthermore, due to the above mentioned plastic properties

Fig. 10D.10. This three dimensional T.C. Scan reconstruction shows a proximal displacement of the fibular head in a subacromial location. Anatomical mismatching and technical problems related to soft tissue repair are the reason of this relatively frequent complication.

of the fibular physis, we observed a progressive improvement of the performance of the reconstructed joint up to several years postoperatively.

In order to maintain a satisfactory pronation and supination, we suggest to avoid a too tight soft tissue reconstruction between fibula and ulna (Fig. 10D.9 A, B). In our experience no ulna subluxation have been noted even at long term follow up despite the apparent laxity of the joint at the end of the surgical procedure.

The functional outcome which can be expected in case of upper humerus replacement is certainly less satisfactory because of anatomical and technical reasons. The proximal fibular epiphysis is quite different in size and shape from that of the humerus and the biomechanical features of the gleno-humeral joint do not promote a significant remodeling, as it can be observed in case of wrist reconstruction. In addition, the soft tissue repair around the fibular head is not always adequate to provide a sufficient stability to the joint with the consequence of a proximal migration of the fibular head in a subacromial position (Fig. 10B.10).

However, the functional impairment claimed by the patients is usually limited to a reduction of abduction which in our experience ranges between 80° and 110°. The overall range of motion resulted to be adequate to accomplish daily activity, including sports involving the upper limb, in the majority of the patients.

As far as the morbidity at the donor site is concerned, damage to the motor branches of the peroneal nerve is the most common and severe complication. As above mentioned, the distribution of the nerve around the vascular bundle sometimes forces the surgeon to consciously interrupt some muscular branches in order to dissect the vessels. In that eventuality, neurorraphy or direct neurotization of the severed branch can usually provide a good functional recovery. In our experience the majority of the patients suffered only a temporary palsy of the peroneal nerve.

The restoration of the knee joint stability is a second critical point. The lateral collateral ligament must be preserved and meticulously reinserted into the lateral aspect of the methaphysis of the tibia by means of transosseous stitches. The residual strip of the tendon of biceps femoris should be used to reinforce the ligament. Such a reconstruction resulted to be reliable in all the cases and no patient claimed instability of the knee joint.

Conclusion

Epiphyseal transfer is a new tool in the armamentarium of microvascular bone reconstruction and offers the attractive possibility to reconstruct long bone defects and to prevent future limb discrepancy in one stage operation. Its clinical application is reserved to those cases where the original epiphysis has been resected or destroyed for traumatic, congenital or neoplastic reasons. The specificity of indication and some doubts on technical aspects account the relative rarity of reports referring to clinical series in the international literature. Our experience, however, allowed to refine the operative technique and to check its reliability on the basis of the observation of 20 patients who underwent surgery over a period of eight years. The majority of the vascularized fibulae showed continual and consistent axial growth after their transfer in heterotopic location and resulted to be the best available option in dealing with such a complex clinical problem.

The described technique is ideal in case of replacement of distal radius where excellent results can be achieved in terms of growth and function, while the reconstruction of the proximal humerus still presents some unsolved problems. Nevertheless, also in this anatomical district, such a procedure has the ability to restore the growth potential and provides better functional results than those which can be expected with other surgical options.

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Microsurgery in Congenital Hand Malformations

G. Foucher, K. Malizos, J. Medina

Microsurgical skill is a basic requirement for any hand surgeon willing to treat properly congenital malformations. In congenital deformities, surgeons, used to postpone operative treatment, waiting until growth and larger anatomical structures made tissue handling easier. Currently, there is a definite trend to correct them at much younger age, in early infantile life to benefit from the plasticity of the brain which allows better remodeling of the anatomical structures and much higher functional integration. Buck Gramcko[5] has demonstrated remarkable remodeling in his cases with pollicization at very early age.

In the management of congenital absence of pinch function in the hand we have tried reconstruction before pinch pattern is established, which means before one year of age. This approach has the added benefit of relieving the anxiety of the relatives at the price of a more demanding technical skill from the surgeon and less postoperative cooperation from the child.

Magnification with 4.3X loupes is usually sufficient for the majority of operations employing microsurgical techniques in the reconstruction of congenital deformities, but in some special circumstances the operative microscope is necessary.[2]

Potential applications of the microsurgical techniques are: *arterial repair* after an iatrogenic arterial lesion such as in complex syndactyly with distal bifurcation of the artery, when sequential clamping demonstrates peroperatively that both neighboring fingers have insufficient perfusion. Although uncommon, twice we have encountered the necessity for an interposed *vein graft* after vascular tumor excision. *Intraneural neurolysis* of interdigital nerves is a mandatory technique in all cases of pollicization.

Free tissue transfers in reconstructing congenital hand malformations have fewer indications such as in case of contraindication or insufficiency of local and regional (island forearm) flaps. *Congenital pseudarthrosis* is very rare in the upper extremity but presents a true indication for a free vascularized bone transfer. On the other hand, in selected cases of congenital malformations of digits or thumb as in constriction band syndrome, transverse deficits, adactylous hand or very complex forms of syndactyly, *toe transfer* offers a very good reconstructive solution. Although this technique is currently well established in traumatic amputations, only a few publications deal with congenital cases.[6,12,17,20,21,28] In the following we discuss the technique, indications and results of total and partial toe transfers.

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Technique of Toe Transfer in Congenital Malformations

The current trend in the reconstruction of congenital malformations of the thumb and the digits is to operate early prior to completion of the first year of age. There are two major difficulties both at the hand and the foot level, the tedious dissection of the miniature anatomic structures into the rich subcutaneous fat and a constant risk of a spasm which is difficult to manage in the babies. Prevention of spasm goes through careful central monitoring of core body temperature and slight elevation of this temperature around 38° C during the operation with a warming blanket.

We favor a single team sequential approach to both recipient and donor sites, to ensure that the length of all anatomical structures is appropriate and matches for transfer without vein or nerve grafts. This has also been proven practical and time saving. Contrary to our technique in traumatic cases, in congenital malformations with hypoplasia, we begin with dissection on the recipient hand site due to frequent anatomical variations.

The surgical approach to the hand varies according to the type of malformation and the site of the transfer. In congenital band syndrome all structures are present and normal as with traumatic amputations; in hypoplastic hands, like symbrachydactyly, a number of anatomical variations may be present. The flexor tendons are usually found attached to the extensor at the distal part of the metacarpal bones. Flexor tendons tend to form a mass, and it is necessary to dissect all the mass and cut their distal insertion to provide some course of motion. The median nerve is frequently absent and compensated by larger dorsal nerve branches (radial and ulnar); they are frequently used as recipient nerves but some palmar branches of the ulnar nerve could also be used. The ulnar or the radial artery are approached through a zig-zag incision to allow closure in a V-Y fashion to decrease vessel compression. This facilitates also the dissection of a dorsal vein. In cases where no veins are found near the artery, a transverse incision is performed dorsally at the wrist crease level to locate a dorsal vein. When the preparation of the hand has been completed, the length for each anatomical structure and most importantly that of the neurovascular bundle is marked and the tourniquet is deflated prior to moving to the donor foot level.

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In a previous review of our patients[11,16] we have found that there was no postoperative vascular crisis when more than one artery was nourishing the transferred toe. With this experience, we always try to dissect all available arteries of sufficient diameter. This is possible only through a unique dorsal approach to avoid a tedious dissection in the plantar fat.[7] First the great saphenous vein is prepared, trying to save as many draining veins as possible. Then the dorsalis pedis artery is easily found, by lifting the extensor hallucis brevis. Proceeding distally the first dorsal metatarsal artery is dissected always running on the dorsum of the intermetatarsal ligament. When present it is immediately dissected from distal to proximal as it frequently passes through some part of the inter-osseous muscle.[19] In the preparation of the second toe an early proximal osteotomy of the second metatarsal bone allows easy dissection of all anatomical plantar structures of the first and second space. This maneuver also facilitates foot closure at the end of the procedure. The plantar artery of the second space, an artery which has been overlooked in the literature, has proved to be constant in our experience and of good diameter.[7] Frequently, the two arteries of the first space and the plantar artery of the second are dissected in continuity with the dorsalis pedis, the proximal communicant artery and the plantar arch. A long segment of plantar nerves and flexor tendons could also be procured into the transfer.

When the toe is completely dissected and remains on its vessels, reperfusion is allowed for sufficient length of time prior to the transfer to avoid ischemic damage. This time is used to assess precisely the length of the different structures and to definitively select the exact recipient levels. If the metatarsophalangeal joint is incorporated into the transfer, a palmar tilt of more than 40° is mandatory to provide a functional range of motion (in a joint working mainly in hyper-extension); this is provided through an oblique cut of the metatarsal neck, protecting the growth plate. The order of repair is classical but could vary from case to case. After bone stabilization (usually with 0.6 K-wire) and periosteal suture, extensor and when possible intrinsic muscle repair is performed. The flexor tendon(s) are then sutured, usually by a "fish mouth" technique (trying to avoid repairing of the superficialis and profundus tendons a the same level). Nerve sutures are generally the next step, followed by distal skin suture to facilitate a good adjustment of the vessel length. The last step is the anastomosis of the artery and vein. Usually a "long" transplantation[29] is performed using the radial artery for the thumb or the ulnar artery for long finger reconstruction. Sometimes the segment of dorsalis pedis in continuity with the plantar arch could be interposed in the recipient artery as a "T" graft, with two end-to-end sutures allowing to reconstruct the recipient vessel and maintain a physiological flow in the toe.[8] The long saphenous vein is sutured to a recipient vein at the wrist level through a short dorsal transverse incision to decrease scarring on the dorsal aspect of the hand.

Then the tourniquet is released and during revascularization of the hand, the foot is closed with intermetatarsal ligament repair and skin suture.

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The dressing has to be carefully performed to allow skin monitoring but to avoid slipping from the cast. In our practice no special postoperative regimen is used; a simple "Chinese" lamp (an ordinary light bulb) allows warming up the transplantation and enhances its capillary refilling. In case of an uneventful course the dressing is not disturbed until three to four weeks. Splinting to improve passive range of motion is begun at seven weeks. No formal program of rehabilitation is recommended, but exercises are encouraged sometimes with bandaging of the opposite nonoperated hand.

Indications

Congenital malformations with arrest of development (group 1), undergrowth (group 5), and congenital band syndrome (group 6), in the classification adopted by the International Federation of Societies for Surgery of the Hand may be true indications for a toe transfer. The congenital band syndrome is a "true" congenital amputation which means that all anatomical elements are easily found at the stump level. Isolated thumb involvement is rare but is a clearly defined indication. Frequently in this syndrome adequate stump length of the thumb or finger remains to provide a good pinch and grasp. Contrary to Gilbert[20] we think that a toe transfer, as a cosmetic indication, is of marginal interest as it is never really appealing.

In the major group of cases with the indications described above some hypoplasia or true aplasia of anatomical structures creates technical difficulties and in some cases less than optimal functional results. However this classification does not allow us to specify the exact indications and it is to the credit of German authors[1,4] to have introduced the sub-classification of symbrachydactyly, which has been recently added in the IFSSH classification. This entity can be clinically distinguished from transverse arrest and from cleft hand. Symbrachydactyly is primarily a unilateral, nonhereditary bone defect, sometimes associated with Poland syndrome. It involves the index and middle fingers, extending ulnarly, the thumb remaining present in the monodactylous type; there is a proximal hypoplasia of the entire limb and distally nubbins with rudimentary nails are noticed. This group was the main indication in our series of 65 toe transfers, representing 45 of them. According to our experience, when there are two opposable fingers there is no indication, instead web deepening, derotation-osteotomy and removal of floating, hypoplastic fingers are sufficient to allow good function.

In the peromelic type and in transverse growth arrest, "distal" implantation of two toes has been sometimes functionally disappointing, leading to difficulties in the manipulation of small objects and providing a weak "pincer". An alternative approach, when there is good wrist mobility, is more proximal implantation. We have modified[14] the Furnas[18] and Vilkki[26] procedure consisting in implanting a great toe or a second toe on the lateral aspect of the diaphysis of the radius. Instead, we insert a second toe in front of the small "palm", on the anterior aspect of the radius, distal to the epiphysis.[14] This has several advantages: it gives us the opportunity to use more tendon transfers, easily available in this proximal site, to better balance the toe. The mobility of the wrist facilitates a good pinch, compensating for the usually limited mobility of the second toe (32° in our experience). A deep web is provided by lifting a flap distally based on the hand, the dorsal aspect of the toe being covered by a dorsalis pedis flap. We have been able to avoid skin grafting of the dorsum of the foot by using a rotation flap. A relevant point is to maintain the metatarsophalangeal joint in hyper-extension, in a technique similar to the one described by Dieter Buck Gramcko[5] for congenital pollicization. It avoids a distal "Z" deformity of the toe with IP flexion.

Less frequent indications are monodactylous hands seen in the ultimate stages of ulnar deficiency or central deficiency. In an exceptional application we have performed one transfer in a girl already amputated in another institution for a macrodactyly.

Transfer of a *vascularized joint and epiphysis* provides special possibilities[6,10,17] in the case of the hypoplasia of the first phalanx of the thumb frequently associated with the monodactylous type of symbrachydactyly. In such cases there is plenty of soft tissue and a simple nonvascularized phalangeal toe graft is usually proposed. However, when combined with a second toe transfer for finger reconstruction, it does not provide the necessary growth potential to keep the pace of the growth of a second toe. Interposition of a vascularized epiphysis provides length, mobility and provisional growth.

Another rare indication is thumb hypoplasia. There is no doubt in anyone's mind that nothing can be as good as a pollicization in advanced thumb hypoplasia from stage IIIB to V in the Blauth classification,[1,3] modified recently by Manske.[23] This author separated in group III those with a first carpo-metacarpal joint (IIIA) from those without (IIIB), proposing reconstruction in the first sub-group and pollicization in the second. We generally agree but we faced two circumstances where an alternative proposition was useful. One is a late consultation of an adolescent coming for improvement of a nonfunctionally-excluded hypoplastic thumb stage IIIB. The other is a definite and repeated refusal, by the parents, of the index pollicization in a stage IIIB, due to the "good appearance" of the hypoplastic thumb. There is no reason, in such cases to "punish" the baby, and a complex, multi-stage operation could be of some benefit, encompassing (as a first step) a free vascularized epiphysis and joint transfer from the second metatarso-phalangeal joint. Other steps are the classical ones for correction of type II encompassing first web opening, MPJ stabilization and opposition transfer as well as those of type IIIA, namely extrinsic tendons reconstruction. Such reconstruction gives good stability and mobility sometimes superior to the one encountered in stage IIIA where instability begins to be painful in adolescents.[17]

We have no experience with the operation proposed by Vilkki,[27] in radial deficiency, consisting of transferring a toe to the radial side of the unstable hand.

Discussion

Several general problems concerning congenital malformations need to be stressed. Four aspects are to be dealt with concerning the psychological problems, appearance of the hand, technique and tactics relevant for the transfer and assessment of the results.

It falls to the parents to make the decision of such an operation and it is not always easy, especially if the surgeon honestly explains that use, at least in the majority of malformations of the hand, is different but very effective even without any operation. In fact experience proves that it is easier and faster to schedule a date for operation than to convince parents that any operation has to be avoided due to a nonrealistic goal. The guilty feelings of the parents lead them "to do something", with the secret hope of eliminating the malformation. We have had very positive experience collaborating with a full time psychologist as an integral part of a hand unit helping parents accept the problem. It is also helpful to prevent them from projecting their own anxiety onto their baby.[3]

The cosmetic aspect is also a major concern in both sexes. Usually the goal of such reconstruction is more functional than esthetic but this last point should not be overlooked, and any combination with a cosmetic prosthesis can be discussed with the prosthetist before the operation.[24] We definitely think, contrary to some authors like Gilbert[20] or Kay,[21] that there are no "cosmetic" indications for such a transplantation. In our experience, a toe remains a toe even if it is used like a finger; a flexed position is sometimes encountered at a milder degree than in adults. The tip remains bulky even 10 years later and the nail is far from a normal nail. The range of motion, although better than in adults, remains limited, being only 32° of active motion, and we have seen some so-called cosmetic indications even impairing the function of neighboring normal fingers.

The surgeon must not just know "how" to perform the transfer but needs also to answer several questions concerning: Who is a good candidate? When must it be performed? How many toes are to be transferred? Where is the transfer best situated for optimal function? What kind of result could be expected? This last point is particularly useful to give some realistic limit to the high expectation of the relatives?

How to do it is surprisingly not a major problem, and we have stressed the few differences with a transfer for traumatic cases. If the diameter of the arteries is not a limiting factor for microsurgical anastomosis even in a ten-month-old baby, the four special problems to be anticipated are: heat loss during anesthesia,[6,22] presence of especially dense fat, anatomical variations and frequency of spasm in the per and postoperative course.

One of the major question concerns "when" to perform such a toe transfer. The baby develops bimanual grasp at 9 months and true three digit pinch between one and two years. It is then logical to elect 11 months as the best period to perform the transfer.[9,12,13,15,17,22,25,28] This makes cortical integration, bone remodeling and muscle hypertrophy easier.[5] These advantages largely overwhelm the mandatory technical expertise, a frequent hypertrophic scar and poor postoperative cooperation.

"How many" toes are to be transferred and "where" to implant them remains a matter of debate and has to be based on individual cases. In none of our cases we have we used the index as the recipient site. The majority were transplanted on the middle and ring fingers, the selection depending mainly on the thumb mobility and length. In case of excellent mobility the fourth or even the fifth are preferred to provide a huge grasp and extra mobility from ulnar carpo-metacarpal joints. The decision has to be tailored in more complex situations with hypoplastic thumb, absent finger metacarpal bones, bilateral hand involvement or associated feet anomalies. It is true that a "chuck pinch" with three digits gives better stability in holding small objects. An added advantage is the prevention of MPJ laxity that we have encountered in a few cases of isolated second toe transfer; this laxity was due to the habit of the child putting the hand on the ground, loading the thumb and the radial side of the transferred toe. If a double second toe transfer is contemplated, the choice remains between an en bloc second and third toe transfer from one foot or a separate second toe transfer from both feet. We are convinced that the advantages of the better metatarsophalangeal range of motion that we have observed in our en bloc transfer (all performed in traumatic cases), is outweighed by the sequels of the donor foot. A double transfer from both feet can be simultaneously or sequentially performed. The advantages of the former are to save time and decrease cost (not as relevant in babies as in adults) at the expense of the surgeon's fatigue, increasing risk of failure and anesthesia time. Sequential transplantation allows the indication to be changed, the position of the second transplantation to be shifted or adapted, and a small additional procedure on the first transplantation (material removal, Z-plasty) to be performed.

Finally, results need to be discussed with the parents. As in all congenital cases, they are difficult to assess.[17] Complications and failures could happen, and we had two such failures in our series of 65 transfers. The first one occurred in 1976 and was partially saved by a groin flap. The second concerned the transfer of an abnormal great toe in a tibial aplasia where an amputation was indeed mandatory to fit a prosthesis for walking. True assessment of "successful" cases is not possible before five or seven years of age. Cortical integration with daily use of the operated hand has to be checked from time to time, from the fifth postoperative month, by toy manipulation during the consultation. In our series such "integration" was clear in 55 of the 58 patients having one or two toe transfers (65 transfers). Among them, 47 toe transfers and 7 epiphysis-joint transfers were available for review at a mean follow up of 5.2 years.[17] If sensibility and growth have not been a problem, restrained range of motion was of concern. The range of flexion was not really better than in the adult with a mean 32° and a mean extension lack of 25°. This may not be a problem for long fingers but is unappealing and functionally disturbing in thumb reconstruction. The two-point discrimination recovers adequately in a mean 5 mm, (despite the use in some cases of a neurotization by radial cutaneous nerve branches) and the regular growth with all epiphysis remaining open except in rare cases with early growth arrest.

In conclusion microsurgery has been a major advance in reconstruction of congenital malformations. Rather than changing previous "conventional" indications, toe transfers have filled a gap. It remains however a complex procedure, with potential risk of failure and limited expectation compared to the usual hope of the family. We think that one of the major points is to perform it very early, before the development of "body image" to be sure that the children will integrate it in their daily activities.

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Chapter 12

Traumatic Brachial Plexus Injuries in Adults and in Newborns

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Brachial plexus lesions, most often due to traction injuries, lead to serious functional disability. Profound knowledge of the anatomy of the plexus and of the pathology is required for the clinical evaluation and the choice of the appropriate treatment. A certain number of patients recover spontaneously in the early months following trauma, but for the remaining patients further investigations (CT-myelography, electrodiagnostic studies) should be scheduled without delay so the that injuries requiring surgical treatment would be recognized early.

The first part of this Chapter deals with the brachial plexus lesions of the adult, including the anatomical basis, the clinical examinations, the diagnostic imaging and the electrophysiological testing used for diagnosing the type, level and severity of the lesion. The treatment options and the particular surgical indications complete this part of the Chapter.

The second part deals with the brachial plexus palsy in the newborn. Details on the etiology, the pathogenesis and the obstetrical factors will be presented as well as the clinical assessment, the indications for surgery and the results of surgical treatment.

Traumatic Brachial Plexus Injuries in Adults

Although the first surgical procedure for brachial plexus laceration is dated back in the beginning of the 20th century, only in the last thirty years with the advent of reconstructive Microsurgery, a significant progress has been made in the operative management of brachial plexus injuries by A. Narakas (1977),[1] H. Millesi (1984)[2] and J.Y. Alnot (1987)[3] and others.

Knowledge of the anatomy of the brachial plexus and of the pathological changes of peripheral nerve lesions allows better understanding of the clinical symptoms and the findings of paraclinical diagnostic examination. Classification of nerve injuries on the other hand, is essential for the therapeutic approach and for the evaluation of the results. In the majority of cases, the injury is the result of motorcycle accidents involving young adults and the lesions are usually more severe. Although a small number of patients spontaneously recover in the early months following trauma, the majority of cases with total palsies diagnosed in the emergency department, do not recover spontaneously.

Practically, any patient showing no signs of recovery 30 days after a brachial plexus palsy of traumatic etiology must undergo additional diagnostic investigations [CT-myelography and electromyography (EMG)], so that the lesions can be classified and the best therapeutic approach can be selected. Surgical reconstruction is necessary for fourth and fifth degree nerve lesions according to Sunderland's classification[4] whereas conservative treatment is recommended for the remaining lesions.

Anatomical Basis

The brachial plexus (Fig. 12.1) is composed of the anterior primary rami of the last cervical nerves (C5, C6, C7, C8) and of the first thoracic nerve (T1):

- Anterior roots of C5 and C6 join to form the superior trunk.
- Anterior root of C7 forms the middle trunk.
- Anterior roots of C8 and T1 join to form the inferior trunk.

Each trunk splits into an anterior and posterior division:

- The anterior divisions join to form two anterior cords (lateral and medial) and their terminal branches: musculocutaneous, median and ulnar nerves.
- The posterior divisions join to form the posterior cord and its terminal branches: axillary and radial nerve.

Several nerves arise proximal, at the level of the roots or trunks. Their examination offers valuable information for the level of the injury:

The long thoracic nerve arises very proximally from the roots C5 and C6 and sometimes C7 and C8. Lesion of this nerve is a poor prognostic factor in brachial plexus injuries.

The suprascapular nerve arises from the superior trunk: a normal activity of the muscles innervated by this nerve in a traumatic palsy indicates that the injury is situated distal to the origin of the suprascapular nerve in the superior trunk.

The phrenic nerve arises from the C4 root and C5 participates by an anastomosing branch. Hemidiaphragm palsy should be diagnosed by clinical and radiological examination.

The presence of Claude Bernard Horner syndrome indicates a proximal injury involving the communicating ramus from T1 to the stellate ganglion.

Posterior roots are more resistant than the anterior roots as they grip with more rootlets to the spinal cord and are larger. Posterior rootlets are protected by the posterior spinal ganglion and their arrangement on the spinal cord provides higher resistance to traction.

The upper roots are attached to the cervical spine by ligaments between the transverse processes and the epineurium of the roots. The stronger attachment of the upper roots in comparison to the lower roots explains the higher frequency of avulsions of the lower roots. Anatomic variations of the brachial plexus have been described: H. J. Seddon defined the plexus as prefixed when the contribution of C4 is significant and that of the T1 is lacking. On the contrary, the plexus is postfixed when the contribution of T1 is large and that from C4 is lacking or minute. Variations in the length of the roots and in the formation of the trunks have been also described.

The arrangement of the plexus on two different planes, anterior and posterior and the absence of connections between these planes, is very important, especially for the surgeon approaching the injured plexus and performing the nerve grafts:

- The posterior plane is constant and simple and is dedicated to the extension of the upper extremity.
- The anterior plane is complex and variable and is dedicated to the flexion of the upper extremity.

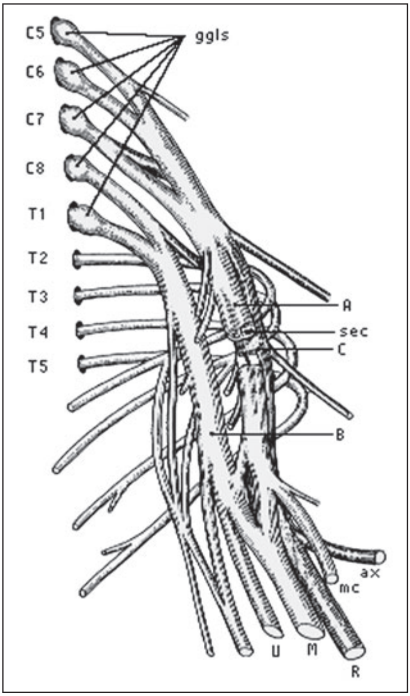

Fig. 12.1. Distal to the ganglions (ggls), the anterior roots of C5, C6, C7, C8 and T1 join to form the superior, middle and inferior trunks. The trunks split into anterior and posterior divisions that join to form the secondary trunks (sec) or cords: the anterior divisions of the superior, middle and inferior trunks form the anterior lateral (A) and anterior medial cord (B) and their terminal branches: musculocutaneous (mc), median (M) and ulnar (U) nerve, whereas the posterior divisions of the trunks form the posterior cord (C) and its terminal branches: axillary (ax) and radial (R) nerve.

Schematically, the anterior part of the root at the level of the scalene muscles corresponds to the anterior plane and the posterior part of the root to the posterior plane. But the distribution of each root to these two planes is variable:

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- C8-T1 may have an extended territory in the posterior plane.
- C7 has a variable distribution in the secondary trunks in the anterior plane.

The mean number of surgical fascicular groups and nerve fibers varies among the roots. C7 contains the largest number of surgical fascicular groups, 6 or 7, whereas C5 contains only 1 or 2 and T1 contains 2 to 3. Each muscle of the upper extremity is innervated by two or more roots.

These variations explain the difficulties in elucidating the topographic level of the lesion and the inconsistency between clinical and pathological findings.

As the same nerve injury may lead to different clinical manifestations, the importance of a complete surgical exploration of the brachial plexus is easily realized.

Mechanisms of Injury

Most injuries of the brachial plexus are related to traction forces.

Four situations leading to brachial plexus injuries can be distinguished:

- Most frequently, a motorcycle accident leads to violent lengthening of the region between the shoulder and the cervical spine and stretching of the roots. In the cases that the arm is abducted in 90° with shoulder

retropulsion the stretching of all roots is maximal, leading to complete brachial plexus injury (with avulsion of the roots). A traction injury in a fully abducted arm is most commonly responsible for C8-T1 palsies.
- Less frequently, a dislocation of the glenohumeral joint leads to injuries of the posterior trunk and sometimes of the terminal branches (axillary nerve, suprascapular or musculocutaneous nerves).
- An open sectioning injury can cut all the nerve structures: epineurium, perineurium, basal lamina and the axon.
- Finally, in a crush injury, all the degrees of lesions of Sunderland's classification can occur.

For traction injuries two mechanisms have been described:
- A peripheral mechanism of traction related to lateral flexion of the cervical spine and lowering of the shoulder girdle.
- A central mechanism related to violent injury of the cervical spine causing rupture of the rootlets from their spinal origin without lesion of the dura.

Pathology of the Lesions

Nerve lesions can be classified in five grades according to Sunderland's classification (1951).[4] This classification is more extensive than the older classification of Seddon (1943) distinguishing three types of lesions: neurapraxia, axonotmesis and neurotmesis.

Both classifications of nerve lesions are applied to isolated nerve trunks and therefore they can be only partially applied to the brachial plexus.

Sunderland's classification includes five degrees of nerve lesion:
1. First degree represents a conduction block at the site of the injury with no macroscopic lesion, corresponding to Seddon's neurapraxia. Recovery is complete and spontaneous.
2. Second degree represents a rupture of the axon with intact basal lamina and without interruption between the neural cell and the periphery. The functional recovery is complete but delayed.
3. In the third degree, the axon and its basal lamina are ruptured. Fascicular continuity remains and the general arrangement of the fascicles in the nerve trunk is preserved. Recovery is delayed and incomplete.
4. In the fourth degree the axon with its basal lamina and the fascicles are ruptured. The regeneration is anarchic and the deficit is severe and permanent.
5. In the fifth degree, the loss of continuity and the irreversible deficit correspond to Seddon's neurotmesis.

Second, third and fourth degrees of Sunderland's classification represent subtypes of Seddon's axonotmesis.

The lesions can be located at any level, from the spinal origin to the division in the axillary region.
- Supraclavicular lesions, located at the level of the roots or primary trunks are the most frequent lesions (75%).
- Retro- and infraclavicular lesions are located at the level of the cords and terminal branches (25%).

A lesion can occur at two levels in about 15% of cases. This percentage underlines the necessity of a thorough exploration of the entire brachial plexus during the surgical procedure.

From proximal to distal, the following lesions can occur:

- Avulsion at the level of spinal rootlets represents a very severe lesion, with no possibility of repair: peripheral traction forces lead to tears of the dura and avulsions of the anterior and posterior rootlets. C7 and commonly C8 and T1 roots become horizontal with abduction of the arm and are frequently avulsed from the spine. C5 and C6 are more securely attached, their course is more oblique at the level of the cervical spine and they are often ruptured more distally in the scalenic region.
- Sometimes, when the mechanism of injury is central, the rootlets are avulsed from the spine without damage to the dura.
- Lesions can be located immediately after the transverse canal; at this level the proximal stumps have sufficient length and can be repaired (grafts).
- Ruptures can also be located more distally, at the level of the primary trunks in the interscalenic region.
- More distal lesions, in the retro- or infraclavicular region are usually associated with skeletal and vascular injuries.
- Lesions of the terminal branches are usually located at the level of relative fixation: quadrilateral space for the axillary nerve, coracoid notch for the suprascapular nerve and entry into the coracobrachialis muscle for the musculocutaneous nerve.

The combination of thirty or more different types of injury affecting the plexus (roots, trunks and terminal branches), with the five degrees of severity of injury (Sunderland's classification) leads to several thousands different variations in clinical cases.

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However, a classification of these lesions is necessary for the selection of the best therapeutic approach and the comparison of the results.

A classification based on the number of involved roots and the level of injury, taking into consideration the completeness or not of the palsy, has been suggested by J.Y. Alnot:[3]

- C5-C6
- C5-C6-C7-C8 Complete or partial palsy
- C7-C8-T1
- C8-T1
- Supraclavicular injury: roots, primary trunks.
- Retro- and infraclavicular injury: cords, terminal branches.

Clinical Examination

Clinical examination associated and the subsequent paraclinical investigations allows preoperative evaluation of:

- the type of nerve lesion: fourth and fifth degree lesions (Sunderland's classification) require surgical treatment whereas the first three degrees require only conservative treatment

- the level of lesion: roots, trunks, terminal branches
- the severity of lesion: violent trauma (motorcycle accident) characterized by high kinetic energy and sudden deceleration may lead to severe brachial plexus injury (root avulsion or fourth and fifth degree lesions).

Clinical examination is sometimes difficult in the emergency department; it should be performed several days after the injury and repeated when the type of lesion is doubtful.

Clinical tests include motor and sensory examination.

The strength of each muscle is evaluated according to the Medical Research Council Motor Grading System (0 to 5).

0: no contraction
1: slight contraction not resulting to motion
2: visible contraction with motion when gravity is eliminated
3: contraction with motion against gravity
4: contraction with motion against resistance
5: normal contraction

Fatigue must be taken into account in the motor examination. Function of the shoulder, elbow, wrist and hand should be evaluated.

Sensory examination must differentiate between subjective and objective disorders and disorders of the autonomous nervous system. It includes assessment of pain, touch, two-point discrimination and proprioception. Pain is evaluated in a subjective scale ranging from no pain to intolerable pain.

Clinical examination is simple in complete palsies but becomes more difficult in partial palsies. Examination should be repeated to locate the nerve lesion and each muscle should be tested.

In the absence of signs of clinical recovery within a period of 30 days from the injury, paraclinical investigations (CT-myelography, EMG) should be performed to obtain a precise diagnosis.

The following factors predict an unfavorable outcome:

- violent trauma with skeletal and vascular injuries
- Claude Bernard Horner syndrome (C8,T1 injury)
- palsy of serratus anterior and elevation of hemidiaphragm (C4,C5,C6 proximal lesion)
- deviation of cervical axis and elevated shoulder
- pain and medullar signs (cord injury)
- severe muscle atrophy

The prognosis is better in the following circumstances:

- brachial plexus lesion after dislocation of the glenohumeral joint. A simple dislocation may lead to a lesion of the axillary nerve or the posterior trunk
- incomplete palsy with a muscular score of 1 or 2 in each root territory

Examination of the Shoulder

Serratus anterior is innervated by C5, C6 and C7. The inferior tip of the scapula moves backward when serratus anterior is paralyzed (scapula alta). The lesion is located at the level of the roots of the brachial plexus (C5, C6, C7 avulsion or rupture). In interscalenic nerve lesions, the serratus anterior muscle remains intact.

Rhomboid muscles (major and minor) are innervated by C4 and C5. When they are paralyzed contraction can not be felt when the patient attempts to push the shoulder backwards against resistance. Rhomboid paralysis indicates rupture or avulsion of C4, C5.

Trapezius is innervated by the spinal accessory nerve and C3, C4. The superomedial angle of the scapula is oriented upwards and the acromion downward in cases of trapezius paralysis and the patient cannot elevate the shoulder.

Supraspinatus muscle is innervated by the suprascapular nerve from the superior trunk (C5). In cases of paralysis scapulohumeral abduction can not be initiated. Integrity of supraspinatus suggests that the lesion is located distal to the upper trunk although the suprascapular nerve can be also injured in the scapular notch.

Infraspinatus muscle is also innervated by C5 through the suprascapular nerve. External rotation of the arm is reduced in infraspinatus paralysis.

Deltoid muscle is innervated by C5 and C6 through the upper trunk and sometimes from C7. The axillary nerve from the posterior cord innervates the posterior, lateral and the anterior deltoid. Anterior elevation of the arm is absent in paralysis of the anterior part of the deltoid; paralysis of the lateral part results in loss of abduction of the arm and paralysis of the posterior part results in loss of posterior arm elevation.

Latissimus dorsi is innervated by C6, C7 and sometimes C8 through the posterior cord. In cases of latissimus dorsi paralysis the arm is unable to move backwards and the strength of adduction and internal rotation is decreased.

Teres major has the same function and is innervated by C5 and C6 from the posterior cord.

Pectoralis major is innervated by C5, C6, C7 and C8 and participates in adduction and internal rotation of the arm. Normal function of the pectoralis major in complete palsy of the limb means that the lesion is infraclavicular.

Pectoralis minor is innervated by C7 and sometimes C8, through the anterior pectoral nerve. Evaluation of the muscle is difficult; the patient is asked to lower the shoulder against resistance.

Subscapularis muscle is innervated by C5, C6 through a superior nerve from the posterior division of the upper trunk and an inferior nerve from the posterior secondary cord. It participates in the adduction and internal rotation of the arm.

Examination of the Elbow

Biceps and brachialis are innervated by C5 and C6 through the musculocutaneous nerve. Flexion of the elbow against resistance with the forearm supinated is used to test these two muscles; the same test with the forearm in neutral position or in pronation is used for the brachioradialis muscle.

The forearm muscles attached to the medial or lateral epicondyle can also act like elbow flexors, with associated flexion of the wrist (Steindler's sign).

Triceps is innervated by C7, C8 through the radial nerve. Evaluation is easy because triceps is the only significant elbow extensor.

Brachioradialis is innervated by C6 and supinator by C7 through the radial nerve. To test these muscles, the activity of the biceps must be eliminated (elbow in 90° of flexion).

Pronator teres is innervated by C7 and pronator quadratus by C8 and T1 through the median nerve.

Examination of the Wrist

Extensors carpi radialis (brevis and longus) and extensor carpi ulnaris are innervated by C6 and C7 through the radial nerve. When these muscles are paralyzed, extension of the wrist is still possible by the finger extensors.

Flexor carpi radialis is innervated by C6 and C7 through the median nerve. Flexor carpi ulnaris is innervated by C7, C8 and T1 through the ulnar nerve. When these muscles are paralyzed, flexion of the wrist is possible through the flexor digitorum superficialis and profundus.

Examination of the Fingers

Only basic function should be evaluated in brachial plexus lesions:

- Extension of the MP joints (thumb and fingers) and abduction of the thumb relies on C7 and C8 through the radial nerve.
- Extension of the PIP joints relies on the intrinsic muscles innervated by C8 and T1 through the ulnar nerve.
- Flexion of the fingers relies on flexor digitorum superficialis and profundus innervated by C7, C8 and T1 through the median (I, II, III) and ulnar (IV, V) nerves.

In summary, the detailed clinical examination required for the evaluation of brachial plexus lesions is difficult both in the emergency department and during the recovery period. The clinical tests should be repeated and the changes in the clinical findings should be recorded.

Paraclinical Tests

In the emergency department plain radiographs of the cervical spine and shoulder are necessary for skeletal evaluation and the diagnosis of concomitant lesions (scapula, clavicle, humeral head, sternoclavicular joint, first rib, transverse process of C7).

In cases of acute ischemia of the upper limb, an angiography in the emergency department will determine the level of the vascular lesion.

If there is no clinical recovery within a period of 30 days after injury, myelography, computed tomography (CT) and neurophysiologic investigations should be performed.

- Myelography confirms the existence of root avulsion with pseudomeningoceles (rupture of the dura sheath and rootlets). Usually pseudomeningoceles are located on the C7, C8 and T1 levels.
- CT is always associated with myelography (CT myelography) and allows visualization of pseudomeningoceles, small defects, irregular roots and interruptions of the rootlets. CT is also useful for the evaluation of the precise aspect of the rootlets at the adjacent level.
- The reliability of CT myelography is approximately 100% and the specificity is 99%.
- A normal CT myelography suggests either a first or second degree lesion (Sunderland's classification) leading to spontaneous recovery or a lesion located on the trunks or further distal, accessible to direct repair or nerve grafting.

- MRI represents the test of the future for the diagnosis of postganglionic lesions as well as peripheral lesions.
- Nowadays, myelography and CT myelography provide information about the proximal lesions of the brachial plexus (root avulsion) but the evaluation of distal injuries relies on clinical examination.
- Neurophysiologic tests are helpful preoperatively in brachial plexus injuries for the decision-making procedure. Electromyography (EMG) is used to record the electrical activity of the motor fibers and also to detect signs of reinnervation. Somatosensory evoked potentials can be used to assess the integrity of sensory conduction from the periphery to the central nervous system. Motor evoked potentials is a promising technique for the assessment of the integrity of the ventral root (motor neuron), but this method is rather uncomfortable for the patient when he is awake. Neurophysiologic tests are useful in establishing the level of the lesion in association to the posterior root ganglion: a preganglionic lesion corresponds to an avulsion of the root whereas a postganglionic lesion corresponds to a distal lesion after the posterior root ganglion. Electric tests are also used for the confirmation of conduction of active potentials through a neuroma. However these tests are not yet very reliable and it is necessary to associate CT myelography and MRI imaging to confirm the root lesion.

Surgical Indications

The therapeutic approach depends on the recovery during the first month and the anatomopathological lesions defined by repeated clinical examination and paraclinical tests (CT myelography, EMG).

- In the majority of cases there is no indication for an emergency surgical exploration, except for acute upper limb ischemia: the ideal strategy in these cases is to graft the vascular lesions and to locate potential nerve lesions, making a secondary nerve repair as easy as possible. In some cases, periscapular anastomoses provide sufficient distal blood supply and allow early secondary vascular and nerve repair. Reconstruction of vascular lesions and improvement of the distal supply is very important for nerve regeneration.
- Associated skeletal lesions should be treated in the emergency department: an anterior dislocation of the shoulder should be reduced immediately. In the majority of cases immobilization of the upper limb in a brace for one week can be followed by rehabilitation (without traction on the roots) to avoid stiffness of the shoulder.
- Surgical exploration is indicated if there is no clinical recovery within a period of 6 weeks to 2 months after trauma.

The whole plexus must be explored (15% of lesions occur at two levels) through a long zig-zag incision extending from the neck to the axillary region (Fig. 12.2) and the surgical technique must be based on the results of preoperative investigations and adapted to the intraoperative findings.

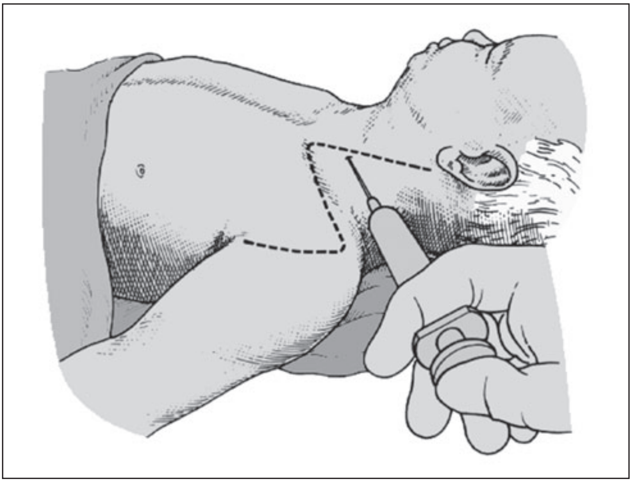

Fig. 12.2. A long zig-zag incision extending from the neck to the axillary region is necessary for the exploration of the entire brachial plexus.

Palsies Resulting from Supraclavicular Lesions

These are the most common (75%) among all injuries of the brachial plexus.

Total Palsy with Avulsion of the Lower Roots (C7, C8, T1)

Repair depends on the number of upper roots spared:

- In the cases that C5 is the only spared root, C5 is connected to the anterior part of the upper trunk through sural nerve grafts and the suprascapular nerve is neurotized by transfer of the spinal accessory nerve. The goal is to obtain stabilization of the shoulder, adduction of the arm (pectoralis major), flexion of the elbow and protective sensibility of the hand.
- In the cases that two roots are spared (C5, C6), it is also possible to graft the posterior cord. In general the anterior part of the root is used to graft the anterior plane of the plexus and vice versa. Some flexion or extension of the wrist or the fingers without pain may be obtained.

Total Palsies with Avulsion of all Roots

- Neurotization is the only possibility: the spinal accessory nerve, the superficial cervical plexus and the intercostal nerves are connected to the musculocutaneous nerve and elbow flexion is obtained in 75% of cases.
- In some cases, spontaneous partial recovery may be noticed: when the recovery is rapid at the C8 and T1 levels but is absent in the upper roots, exploration in the scalenic region and repair of any rupture should be performed, whereas if the recovery is slow and goes from the shoulder to the hand, surgical exploration and neurolysis or repair is indicated.

- After shoulder dislocation a total palsy recovers in 80-90% of cases.

Partial Palsies Involving the C5, C6 or C5, C6, C7 Roots

The hand is normal and in the majority of cases the lesions are located in the scalenic region or in the upper trunks.

- In cases of rupture of C5, C6 in the scalenic region the proximal stumps are transferred to the anterior part of the upper trunk with the use of nerve grafts (sural nerve) and the suprascapular nerve is connected with the spinal accessory nerve.
- In the cases that C5, C6 are avulsed and grafting is impossible, the spinal accessory nerve is used to neurotize the suprascapular nerve in order to stabilize the shoulder and provide a slight external rotation of the arm. Elbow flexion can be obtained with a muscle transfer or with neurotization of the nerve for the biceps, through direct suture with a fascicular group from the ulnar nerve.
- When C5, C6, C7 are avulsed, the same procedures are used to obtain shoulder and elbow function, whereas muscle transfers are used for the wrist and hand function. Another option for this situation is to perform a lateral suture of the upper and middle trunk to the lower trunk, however the results of this procedure have not been reported yet.

Partial Palsies Involving the C8, T1 Roots

In cases that CT myelography indicates an avulsion of C8 and T1 roots, surgical exploration is not justified. However, surgical exploration is necessary for the diagnosis and potential repair of lesions in cases with normal CT myelography and absence of spontaneous regeneration.

Palsies Resulting from Retro and Infraclavicular Lesions (25%)

Two groups can be distinguished:

1. In the first group, in which the diagnosis is difficult, the lesions are located at the level of the cords, behind or below the clavicle and are usually associated with bone and vascular lesions.
   - Lesion of the posterior cord leads to deltoid paralysis and proximal palsy of the radial nerve (elbow, wrist and hand) with motor and sensory signs.
   - Lesion of the lateral cord leads to palsies of the musculocutaneous nerve and lateral component of the median nerve.
   - Isolated lesion of the medial cord is rare with a clinical aspect of high medio-ulnar palsy. The treatment is complex and an osteotomy of the clavicle is necessary to define the lesions precisely. Diffuse lesions, extending from the clavicle area to the middle third of the arm are frequently found and the therapeutic options are limited by the availability of nerve grafts.
2. In the second group the lesions are located at the level of the terminal branches.

Axillary, musculocutaneous, radial and suprascapular nerve lesions can evolve alone or in combination.

In the majority of cases, the axillary nerve is impaired after an anterior and medial dislocation of the shoulder. In 80% of these cases this is a neurapraxia and complete recovery is obtained in 4-6 months.

Combined paralysis of the axillary and suprascapular nerves leads in loss of shoulder abduction. In isolated lesions of the axillary nerve abduction is possible through the supra- and infraspinatus muscles and in these cases the diagnosis is often delayed. Anesthesia or hypoesthesia in the lateral deltoid region always occurs in the previous situations.

The level of the nerve lesion can be located with EMG studies and commonly a rupture of the axillary nerve in the quadrilateral space of Velpeau is found. Treatment with a nerve grafting procedure through double approach leads to excellent results within six months.

The diagnosis is more complicated in cases of distal lesion of the suprascapular nerve or avulsion of the axillary nerve from the deltoid or an associated rotator cuff tear.

Palliative Surgery in Brachial Plexus Palsies

Palliative surgery is sometimes necessary after failure of nerve repair to improve the function of the upper extremity but it can also be indicated at the same time with the nerve surgery.

Palliative surgery must be individualized for each patient and depends on the degree of recovery gained after nerve repair. Intensive rehabilitation to obtain complete passive motion of the joints is essential after brachial plexus injuries. Patient's motivation and ability to cooperate is very important. Restoration of shoulder's stability and elbow's flexion are prerequisites for good hand positioning. The ultimate goal is the restoration of the most basic functions of the hand: pinch and grip.

1. Different procedures can be used to stabilize and to improve the function of the shoulder:
   - Ligament plasty reduces the inferior subluxation of the humeral head and provides slight external rotation of the arm.
   - Arthrodesis of the shoulder is recommended by some authors in cases of deltoid, supraspinatous and infraspinatous paralysis. Ideal positioning is difficult and nonunion is a frequent complication. However, strength is improved after arthrodesis and nerve repair procedures can be focused on the reconstruction of the function of the elbow and hand. The procedure is contraindicated in serratus anterior paralysis.
   - In cases of isolated deltoid paralysis, transfer of the trapezius onto the humerus (Bateman's procedure) provides 30° of abduction.
   - Derotation osteotomy of the humeral shaft is the last solution to avoid abnormal positioning of the forearm during elbow flexion due to the lack of external rotation.
2. Numerous procedures have been used to restore elbow flexion depending on the nerve lesion:
   - In C5, C6 palsies a triceps to biceps transfer (Bunnel 1951) is preferable. Pectoralis minor (Le Coeur 1953) or flexor-pronator (Steindler 1918) transfers can be also used.

• In C5, C6, C7 palsies, a flexor-pronator advancement is preferable. The strength of the transfer can be improved with an associated arthrodesis of the wrist.

• In total palsies a triceps to biceps or a latissimus dorsi transfer can be used.

3. Palliative surgery for restoration of basic functions of the hand (extension of the wrist, flexion of the fingers, adduction flexion of the thumb and extension of the MP joints), depend on the nerve lesions:

• In the cases that C5, C6, C7 are involved and C8, T1 are spared, conditions analogous to high radial palsies, Tubiana's technique can be used:
- Pronator teres (PT) transfer to extensor carpi radialis brevis (ECRB)
- Flexor carpi ulnaris (FCU) to extensor digitorum communis (EDC) and to extensor pollicis longus (EPL)
- Palmaris longus (PL) to abductor pollicis longus (APL) and extensor pollicis brevis (EPB)

• In the cases that C8, T1 are involved (with or without the C7) and C5, C6 are spared, finger flexion can be obtained through transfer of extensor carpi radialis brevis or through tenodesis of flexor digitorum profondus and pinch grip can be obtained through brachioradialis to flexor pollicis longus transfer.

• In cases of total palsies, tenodesis and arthrodesis procedures allow functional positioning of the fingers and the thumb.

Brachial Plexus Palsy in the Newborn

The origin of newborn palsies is traumatic and not congenital; the lesions are caused by the traction applied on the roots during combined lowering of the shoulder and inclination of the cervical spine to the contralateral side.

The diversity of lesions depends on the mechanism but also on the anatomy of the roots (ligaments, angle of attachment, direction of the roots).

The incidence of newborn palsy is approximately 2 per 1000 births and the percentage of spontaneous recovery is around 80-90%. Thus, surgical treatment is only necessary in 10-20% of newborn palsies.

Brachial plexus palsy is usually associated with two obstetrical situations:

1) Overweight newborns (> 4000 g) in cephalic presentation. In these cases, dystocia of the shoulders leads to hyperextension of the head and traction of the plexus. Manipulation with forceps in these cases sometimes leads to a fracture of the clavicle.

2) Breech presentation, usually combined with low birth weight. The higher nerve roots are frequently involved and the lesions are more severe than those occurring in cephalic presentation.

Bilateral obstetrical palsy can occur.

Clinical Presentation

The diagnosis at the time of the birth is relatively easy when forceps have been used during the delivery.

Hypotonic paralysis and muscle atrophy are poor prognostic factors. It is important to examine the controlateral upper and lower limb in order to rule out the dreadful situation of neonatal tetraplegia.

Two basic clinical types of newborn palsy can be identified:

Paralysis of the Upper Roots

The upper limb is held in internal rotation and pronation and active abduction is not possible. The elbow is slightly flexed (paralysis C5, C6, C7) or fully extended (paralysis C5, C6) and the wrist and sometimes the fingers are flexed.

Complete Paralysis

The upper limb is flail and the hand is clutched, without any tonus. There is sensory and vasomotor impairment. Phrenic palsy and Claude Bernard Horner's sign indicate a severe lesion and particularly an avulsion of the roots.

Radiographs may depict a fracture of the clavicle or of the upper humerus.

The evolution is variable and a re-evaluation is necessary at the third week. At this time one of the following situations can be recorded:

- In cases of paralysis of the upper roots there is a partial recovery.
- Complete paralysis evolves towards a paralysis of the upper roots or remains unchanged.

An EMG and occasionally a myelography define the lesions very precisely; they can be performed safely at the third month.

Physical therapy is initiated immediately after birth to avoid internal retraction of the arm. Splints in external rotation and abduction of the arm are dangerous and their use should be avoided because they lead to abduction contractures.

The natural history of brachial plexus palsy (Tassin, 1983) indicates that spontaneous recovery and good final result should be expected in infants with initial contraction of the biceps or the deltoid before the age of 3 months. Thus, surgical exploration in newborn palsy is indicated when there is no clinical recovery of the biceps at three months of age. [5]

Strategy of Repair

Paralysis of the Upper Roots

- Rupture of C5, C6

In the majority of cases a neuroma is found between the roots and the division of the upper trunk, at the level of the clavicle.

After resection of the neuroma, the gap is bridged with grafts from the two sural nerves; the grafts are secured in place with the use of fibrin glue (Fig. 12.3).

The results are good if at least one root (C5 or C6) can be grafted. After nerve repair, good or excellent results on the shoulder are expected in more than 50% of cases.

Sometimes, the quality of the root can not be judged and the surgeon has to choose between leaving the root in place or neurotizing it.

- Avulsion of C5, C6

In these cases the only possibility is the neurotization of the upper trunk with the spinal accessory nerve, the intercostal nerves or even the contralateral C7 root.

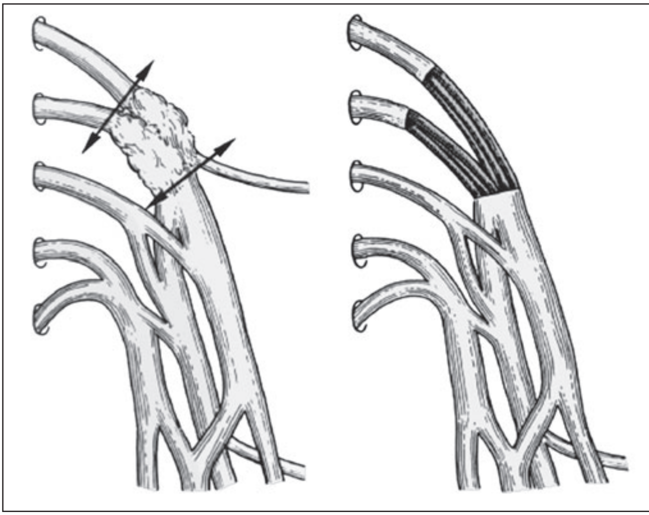

Fig. 12.3. In C5-C6 ruptures, after excision of the neuromas, the proximal stumps can be connected to the upper trunk with the use of nerve grafts.

Lateral sutures of the upper trunk to the middle or the lower trunk have been performed recently but the results have not been reported yet.

Complete Paralysis

- Rupture of C5, C6 and avulsion of C7, C8 and T1

Reconstruction is complex in these cases and grafting procedures are associated with neurotization procedures. The aim is to obtain a functional hand, elbow flexion and shoulder stability (Fig. 12.4).

- Avulsion of four roots

In cases that one root is spared, grafting and extraplexal neurotization from the spinal accessory nerve or intercostals can be performed (Fig. 12.5). Recently, an end to side nerve coaptation to the spared root has been performed with glue.

- Avulsion of all roots

Exploration of the plexus should be complete in these cases and an osteotomy of the clavicle is necessary to dissect lower roots. Dissection should be as proximal as possible to define the lesions precisely.

A useful hand can be obtained with neurotization procedures in more than 50% of the cases.

At the end of the surgical procedure the child is placed into a protective splint immobilizing the upper body, the neck and head (Fig. 12.6).

Secondary Reconstruction

The infant is followed each year after the nerve repair, and secondary surgical procedures are performed depending on the progress of the functional recovery after rehabilitation.

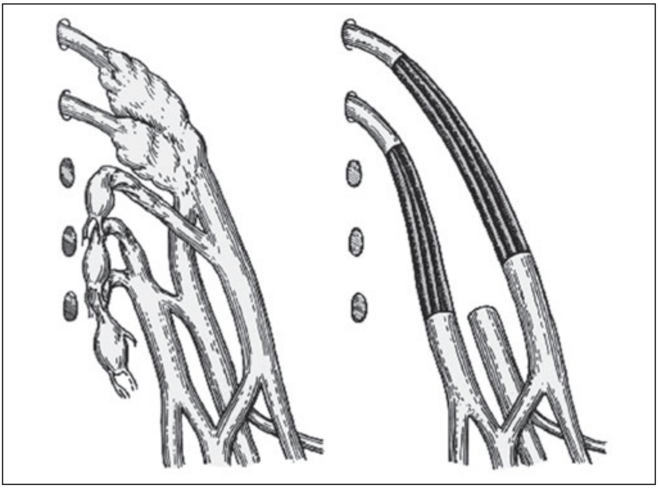

Fig. 12.4. In C7-C8 and T1 avulsions combined with C5-C6 ruptures, the proximal stumps of C5 and C6 are connected to the anterior-lateral and anterior-medial cords with the use of nerve grafts.

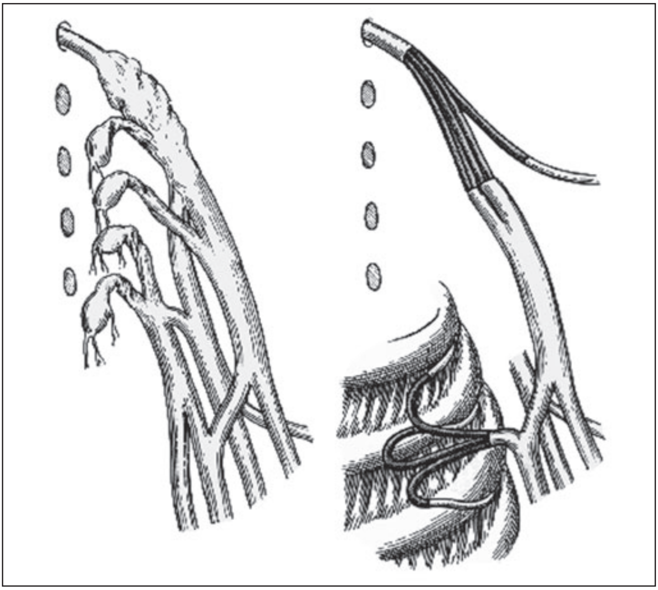

Fig. 12.5. In total pulsies with avulsions of all the roots except the C5, a graft connects C5 root to the anterior-lateral cord and the intercostal nerves are used to neurotize the anterior-medial cord.

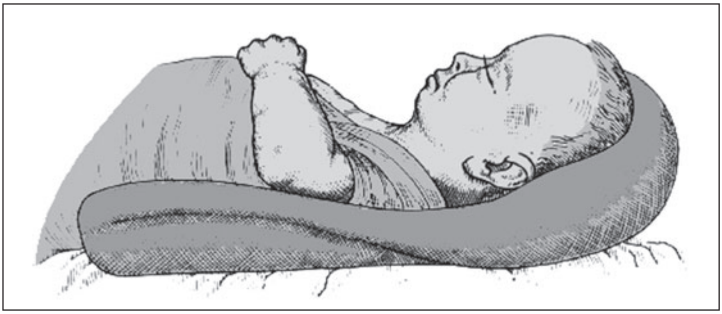

Fig. 12.6. A protective splint immobilizing the upper body, the neck and head is used after the surgical procedure.

- Medial contracture of the arm can be treated with subscapularis release.
- The lack of abduction and external rotation can be improved with a latissimus dorsi transfer to the cuff.
- In case of a poor result at the level of the shoulder, a trapezius transfer can be proposed (if the spinal accessory nerve has been spared) to improve abduction of the joint.

Conclusion

Newborn palsy is a traumatic lesion occurring in overweight babies in cephalic presentation or in small babies in breach presentation.

Spontaneous recovery of biceps contraction within three months predicts a good final result. No recovery of the biceps at three months of age is an indication for exploration and microsurgical reconstruction of the plexus. Surgery leads to better results than spontaneous recovery. If there is only a small recovery at six or nine months of age, the final result will be poor. Although a surgical procedure would offer better chances of functional recovery than the spontaneous in the above cases, it is often too late for the family to accept a surgical procedure.

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Microvascular Reconstruction of the Head and Neck

Peter C. Neligan

Head and Neck Reconstruction

Head and neck reconstruction presents unique challenges to the reconstructive surgeon. Because the head and neck region is so visible, defects of any kind in this area are difficult to hide and the demands on our reconstructive skills are greater than they are elsewhere in the body where cosmesis may be less vital and function less specialized. The head and neck area includes both static and dynamic structures. In addition, it contains organs of special function such as the tongue, the nose, the ears, the lips and the orbital contents including the eyelids.

While bony structures elsewhere in the body are related to structure and load, the bony skeleton of the head and neck area includes these functions but, in addition, includes the jaws which have a very specialized function and unique reconstructive requirements. While reconstruction of specific areas of the head and neck will be discussed in detail there are general principles which apply to all regions. Reconstruction involves a composite reorganization of tissue, often imported from distant sites on the body into a replication of what has been resected. We must therefore start with an analysis of that tissue. The craniofacial skeleton fulfills several functions. It is responsible for the contour of the head and face. As well, it provides protection to vital structures, most notably the brain, Finally the skeletal structures of the upper and lower jaws provide a very specialized functional role, that of mastication, which is unique in the body. The soft tissues of the face are also unique. They comprise external cover, which, in some cases, is specialized, as in the eyelids. The facial muscles provide a unique and very delicate function to animate the face, driven by a complex motor nerve, the facial nerve. This nerve sometimes has to be sacrificed to execute an effective ablation. Apart from external skin cover we frequently also have to replace mucosa. Not infrequently all of the above elements have to be replaced. The principles that guide us are several and basic:

1. We should wherever possible replace excised tissue with like tissue. This generally means local tissue and while this is not always available, we should, whenever possible, use it. Local tissue provides the best match both cosmetically and functionally.
2. Our reconstruction should not interfere with treatment of the patient's presenting illness. If, for example the patient requires some sort of adjuvant therapy, we should ensure that our reconstructive choice will have healed expediently in order not to delay that process.

3. While the simplest treatment is not necessarily the best we should, nevertheless, choose an option that has a reasonable chance to succeed. Technical feasibility alone is not an indication for any procedure.

Scalp Reconstruction

The scalp has several unique characteristics. The most obvious is that it is hair bearing. Secondly, the structure of the scalp, consisting of highly vascularized skin and subcutaneous tissue in close affinity with the rather unyielding underlying galea means that long narrow flaps can be designed with reasonable safety. For smaller defects local flaps are the best option as they fulfil all the criteria we outlined above i.e., replacing like tissue with like and keeping things simple. If one has the luxury of being able to stage the reconstruction, tissue expansion is extremely useful in this area as it allows one to expand the adjacent hair bearing skin. If one is dealing with a malignant process it may not be reasonable to use tissue expansion at the time of tumor excision. If a graftable bed remains following tumor excision however, a temporary skin graft followed by staged expansion and reconstruction is often the best option. In situations where there is no graftable bed, such as when the excision has exposed a significant amount of caLVArium that cannot be closed by local flaps, free tissue transfer is often the only option. However it should be emphasized that free tissue transfer is the ultimate option. Usually, unless the defect is extremely large, it can be closed with the use of a local rotation flap even if the donor defect has to be grafted. In this situation the graft can, once again, be excised through the use of subsequent expansion and local flap advancement.

Free flap scalp reconstruction is, nevertheless, still occasionally the only option. As these defects are usually large, a large flap is required to cover the caLVArium and my personal choice is a free latissimus muscle flap with a split thickness skin graft. In this situation a sheet graft provides the best aesthetic result as a meshed graft maintains a reptilian appearance and is unsightly. These flaps are usually bulky and the immediate postoperative result is often less than optimal. However within a very short time, muscle atrophy occurs and the ultimate outcome is very acceptable. If the forehead is involved I tend to favor the scapular flap. This is because the texture and color match of the scapular flap is very suitable for reconstruction of facial skin in general whereas the grafted latissimus muscle tends to remain pale.

Reconstruction of the Calvarium

The skull itself not only provides contour for the head but it protects the underlying brain from repeated trauma. Occasionally the calvarium itself is removed. This may occur as a result of tumor surgery, trauma or as a consequence of previous surgery. Whatever the cause the decision must be made as to

a. whether or not the calvarium will be reconstructed;
b. whether this reconstruction will be accomplished at the time of wound closure or secondarily and
c. how this reconstruction will be accomplished.

These decisions will be based on such issues as

1. the age and general condition of the patient;
2. the patient's prognosis;
3. planned postoperative radiotherapy;

4. the presence or absence of infection.

There are obviously many ways to reconstruct the calvarium; rib grafts, split calvarial grafts, methyl methacrylate or other bone substitute, titanium mesh. The choice of technique will depend on the factors outlined above as well as on the availability of suitable donor bone. Generally, in the oncology patient this reconstruction will involve soft tissue cover as well as bone. In these situations the same choices are available and in my practice the latissimus muscle with split thickness skin graft is the first choice. In certain patients wound closure can be achieved with flap cover alone without bony reconstruction. This is usually the choice in older patients with limited life expectancy and in whom the risk of significant trauma to the skull is unlikely or can be minimized,

Cranial Base Reconstruction

A cranial base lesion, for purposes of this discussion, is defined as one that requires both an intracranial and extracranial approach for its ablation. Our reconstructive goals in these lesions are very specific since, almost by definition, this type of resection leaves the dura exposed to the upper aerodigestive tract. These resections frequently also involve resection and repair of the dura and this repair is, in turn, exposed to the aerodigestive tract. The goals for reconstruction of the cranial base are shown in Table 13.1. There are several options for repairing the dura. The commonly used options in our practice are

1. the pericranial flap;
2. the anterior rectus sheath;
3. fascia lata grafts and
4. fibrin glue (Tisseel®).

The latter is used as an adjunct to the other techniques to ensure that the dura is truly sealed and the risk of CSF leak minimized. The pericranial flap when used is raised prior to the craniotomy and protected during the case so that it can be used to seal the dura at the end of the procedure. This is usually applicable to anterior dural defects. It is important to remember that when the bone flap is replaced the blood supply of the pericranial flap must not be compromised. One of the most important functions of the reconstructive flap is to obliterate dead space and to this end it is important to suspend the flap from the cranial base to ensure that the flap is directly in apposition to the dural repair. The use of free tissue transfer in the cranial base has minimized the risk of CSF leak, meningitis and abscess formation and allows us to operate on and ablate tumors that were previously considered unresectable. The workhorse flap in this area is the rectus abdominis, usually as a muscle flap but occasionally as a myocutaneous flap. The tendinous intersections of this muscle can be used as a means of placing secure sutures in the flap by which it can be suspended from the skull base. These flaps are usually revascularized from the superficial temporal vessels or, alternatively, from vessels in the neck.

Reconstruction of the Maxilla and Midface

If there is any region in the head and neck where our reconstructive techniques are lacking it is in the maxillary defect. The maxilla is a unique bone, providing support for the orbital contents above, fashioning the roof of the mouth below and the lateral wall of the nasal cavity medially. As well as this it contains the maxillary

Table 13.1. Goals of cranial base reconstruction

1. Provision of tight dural seal;
2. Obliteration of dead space;
3. Suspension and support of neural structures;
4. Provision of bone and/or soft tissue cover;
5. Maintenance of function
6. Maintenance of cosmesis.

antrum which plays a significant role in the normal physiologic function of the upper airway. It is covered by skin on the outside, the orbicularis oculi muscle and eyelids superiorly and mucosa elsewhere. The techniques used in reconstruction of the maxillary defect have not yet reached the sophistication of state of the art mandibular reconstruction and are still evolving.. In many instances we are, in effect, filling a hole. The type of reconstruction will obviously depend on the defect. It is important to identify the requirements of the reconstruction. If bony reconstruction is required which area needs to be reconstructed? This will depend on the type of maxillectomy defect (Table 13.2). Type 1 maxillectomies may not need any reconstruction. Type 2 maxillectomies can be treated with a dental obturator. This has been the classical treatment for these defects and while it works quite well, its success depends on the fit of the obturator. Patients occasionally complain of excessive crustiness in the maxillectomy cavity and hygiene may be problematic. As well, there is a hollowing of the cheek that creates a cosmetic deformity that may or may not be significant but is quite variable. These defects may also be reconstructed with a flap such as the rectus abdominis. This fills the cavity and can reconstruct the palate nicely however it may create difficulties for the prosthetist in fitting a dental prosthesis. Palatal reconstruction using this technique usually involves holding the palatal portion of the flap in position with a dental plate for six weeks postoperatively during which time the muscle mucosalizes. Long-term results are variable because of the unpredictable amount of atrophy which the muscle undergoes. This is particularly relevant in patients who undergo postoperative radiation. In these patients muscle atrophy is compounded by fibrosis and contracture of the rectus muscle secondary to the radiation. Alternatives to this technique include the use of flaps such as the scapula or radial forearm with separate skin paddles for palate and lateral nasal wall. The iliac crest with internal oblique can also be used. It provides both bone, which may later be used as a platform for osseointegrated implants for dental rehabilitation, as well as the bulk of the internal oblique muscle. In this situation the muscle is, again, allowed to mucosalize intraorally. Because of the bone the effects of muscle atrophy on contour are minimal. Reconstruction of the orbital floor is important if dystopia is to be avoided. This can be achieved with bone grafts such as split calvarial grafts or with titanium mesh. Using soft tissue flaps alone to support the globe has proved disappointing probably because of the subsequent muscle atrophy which has already been discussed.

Soft Tissue Reconstruction of the Midface

As with all other areas, the midface is best reconstructed with local tissue and we must not forget the cheek rotation flap and the cervicofacial flap. These flaps

Table 13.2. Classification of the maxillectomy defect

Type 1	Medial maxillectomy only, palate and orbit intact
Type 2	Partial maxillectomy, orbit intact, palate resected
Type 3	Partial maxillectomy, palate intact orbital floor resection, eye intact
Type 4	Total maxillectomy including palate and orbit al floor, eye intact
Type 5	Total maxillectomy , palatal floor, orbital floor and orbital exenteration

provide the best possible tissue for reconstruction, replacing what has been resected with exactly similar tissue. In the male, one of the limitations is the risk of moving hair bearing tissue from the beard area to the infra-orbital region or even onto the lower eyelid. Another very useful local flap for reconstructing the lower facial region as well as the cheek is the submental flap. The same caveat applies in the male patient where the possibility of transferring hair bearing tissue into a nonhair bearing region must be considered. Where local tissue is not an option, free tissue transfer is the remaining choice. Once again, color and texture match are an important consideration. The size of the defect may dictate the choice of flap. In through and through defects of the cheek the flap may need to be folded on itself to provide both external skin cover as well as mucosal lining. In this situation the flap must not be too thick. Options include the radial forearm flap, the scapular flap and the anterolateral thigh flap. Of these the scapular flap provides the best color and texture match for the face. The radial forearm and anterolateral thigh flaps tend to be very pale.

Reconstruction of the Oral Cavity

The oral cavity is a unique anatomical site that is multifunctional. It is the inlet of the aerodigestive tract. It is also vital to the process of normal speech production. It accommodates many specific and highly specialized structures: the mandible and teeth, the tongue, the palate and the oropharynx. Its lining mucosa is bathed in saliva. This mucosa covers muscles that provide the motor functions that facilitate some aspects of speech and swallowing. Furthermore, it is rich in nerve endings which provide us with the special sense of taste as well as exquisite sensation.

When planning reconstruction of the oral cavity there are several considerations to be addressed. Issues such as prognosis; the general medical condition of the patient; and the use or planned use of radiation are important in choosing the appropriate reconstruction. Furthermore, the extent of the resection will help ascertain which type of reconstruction is most suitable. The goal of reconstruction is to allow the patient to maintain function which is such an important factor in maximizing quality of life.

Reconstructive Technique

The reconstructive technique chosen can include multiple modalities but the reconstructive ladder which applies to all defects is also applied in the oral cavity.

This ladder includes direct closure, closure by secondary intention, skin grafting, local flaps, regional flaps and free tissue transfer in ascending order of complexity.

Closure by Secondary Intention

Allowing the wound to granulate is an option in the oral cavity. It must be utilized however in the knowledge that the resultant contracture and scarring will not jeopardize function by compromising mobility. This is a technique which can be applied with other reconstructive options such as when an intraoral muscle flap is allowed to remucosalize. While this Chapter concentrates on microsurgical techniques for head and neck reconstruction it must not be forgotten that traditional techniques such as direct closure, skin grafting and the use of local or regional flaps are also occasionally indicated.

Free Flaps

The reliability of microvascular techniques has made free flaps the reconstructive method of choice for most large defects. Free flaps provide a versatility and diversity of choice in selecting the most appropriate reconstruction. The option of incorporating any tissue type, skin, fascia, muscle, tendon, bone, or any combination of these becomes available. The flap can be tailored to the individual not only in terms of the reconstruction but also of the donor defect left behind. Reinnervation is also an option with many of these flaps. Several flaps are in use but some stand out as workhorses for specific reconstructions. The radial forearm flap provides thin pliable, relatively hairless skin with excellent innervation potential and is by far the commonest flap used to replace intraoral lining. The fibular osseocutaneous flap is generally the flap of choice for mandibular reconstruction. It provides good quality bone in ample supply in combination with a reliable skin paddle which has excellent potential for re-innervation. These two flaps alone will be sufficient for the vast majority of intraoral reconstructions. Other flaps of course will be used and many have specific indications for reconstructing specific defects.

Floor of Mouth

Reconstruction of the floor of mouth requires thin pliable tissue. The extent of the defect will determine which technique is most appropriate. The principles outlined above all apply. Very small defects can be allowed to granulate and remucosalize or may be covered with a split thickness skin graft. Local flaps may be used to good effect in moderate sized defects. These include buccal mucosal flaps, including the facial artery musculomucosal flap (famm flap), tongue flaps and nasolabial flaps. For larger defects the radial forearm flap is reliable and widely used. It has the advantage of being thin and pliable as well as having the potential for re-innervation. The flap may be raised synchronously with the ablation. This saves operative time. Access to the floor of mouth for ablation and reconstruction is generally achieved, except for the smallest lesions, through a mandibulotomy approach. A symphyseal mandibulotomy is preferred. This allows for preservation of the mental nerves. Accurate repair of the mandibulotomy is important. This is achieved either with a plate or with lag screws. Accuracy is assured by applying the fixation before mandibulotomy: the mandible is predrilled either at the site of plate hole placement or lag screw placement. The fixation device is then removed and the mandibulotomy is performed. At the end of the procedure the screws are merely inserted in the predrilled holes to give a perfect reduction.

When planning the reconstruction it is important to ensure that adequate tissue is provided to cover the defect and avoid any potential tethering of the tongue which can cause considerable morbidity. The defect should be carefully measured to ensure harvest of an adequately sized flap. Our flap of choice in this situation is the innervated radial forearm flap. The lateral antebrachial cutaneous nerve is harvested with the flap. Re-innervation of this flap is very efficient and it is thought to improve oral function by allowing the patient to be aware of foodstuff etc. in the reconstructed segment of the oral cavity. This not only makes eating more comfortable but allows for improved oral hygiene.

Xerostomia is one of the problems faced by oral cavity patients following radiation. In an effort to minimize this debilitating side effect jejunal patches and colon patches have been used for floor of mouth reconstruction. These flaps combine thinness and pliability with the capacity to produce mucus. While this works well, the ability of these flaps to withstand radiation is problematic. For this reason they are not widely used.

Tongue

The priorities for tongue reconstruction include airway protection, swallowing and articulation. Tongue mobility is vital for intelligible speech. As well as this the tongue helps to initiate swallowing by propelling the food bolus back into the pharynx. Functional reconstruction of such a vital and dynamic structure is very difficult to achieve. The result of the reconstruction as well as the most appropriate reconstructive choice depends on the size of the tongue resection. The larger the resection the more difficult it is to achieve normal function and the bulkier the flap required to adequately reconstruct the defect. For smaller resections, a thin pliable flap such as the radial forearm flap is ideal and is our first choice. It is important when insetting the flap to ensure that the remaining normal tongue is in no way tethered and is allowed to move optimally. The reconstruction can best be achieved by folding the flap along the lateral border of the tongue and insetting it in such a way that this part of the flap is functionally separate from the portion of the flap covering the adjacent floor of mouth. The lateral arm flap is also a useful flap for tongue reconstruction and has the advantage of being a little more bulky than the radial forearm flap. This is useful when reconstructing a hemiglossectomy defect. It has the disadvantage however of having a smaller and shorter pedicle than the radial forearm flap. It shares the potential for re-innervation with the radial forearm flap

When more than a hemi-glossectomy is carried out, the results of reconstruction become less and less rewarding. As more tongue is removed the chance of producing a mobile reconstruction is diminished. The defect produced by subtotal glossectomy with laryngeal preservation is associated with a high incidence of significant permanent swallowing problems. This is because loss of the propulsive tongue leads to a situation in which food slides down, uncontrolled. When the bulk of the tongue is removed a bulky flap is needed. In our estimation this is the ideal situation in which to use a rectus abdominis myocutaneous flap and is one of the few situations when this flap is used intraorally. The rectus abdominis myocutaneous flap has the advantage of providing bulk. This reduces the risk of inhalation and gives the patient the best chance of regaining the ability to swallow. Functioning muscle flaps have been advocated in order to obliterate the space between floor of mouth and palate during swallowing. However a combination of the flaps discussed above represent the current gold standard.

The Pharynx

As with other areas within the oral cavity, reconstruction of the pharynx demands thin pliable cover. Again, in our practice, the radial forearm flap is the workhorse in this area. The choice of flap will be dictated by the size of the defect Other thin flaps such as ulnar artery flap, the lateral arm flap and anterolateral thigh flap have also been used successfully in this situation. Once again, the jejunum has been successfully used as a patch. As previously mentioned, the limitation of the jejunum has been its poor response to radiation

The Palate

Soft Palate

The soft palate is such a dynamic structure that reconstruction is difficult and its reconstruction has traditionally been nonsurgical, a prosthesis being frequently used to obturate the palatal defect. Fitting such a prosthesis is frequently difficult and the prosthesis may be difficult to wear because of mucositis and xerostomia. This is particularly the case after radiation. Thin sensate flaps such as the radial forearm are best suited to this area. Because the flap is not dynamic however, velopharyngeal competence cannot be achieved unless the flap touches the posterior pharyngeal wall. Urken achieves this by fashioning a pharyngolpasty incorporated within his flap. For large defects, and particularly those that include a pharyngeal defect we have used two flaps in combination to close the defect; a radial forearm flap to provide pharyngeal closure with oral palatal reconstruction and a lateral arm flap anastomosed in sequence to provide nasal pharyngeal closure.

The Mandible

Mandibular reconstruction has evolved over the past 2 decades to become a very reliable though complex technique. The main reason for this advance has been the incorporation of microsurgical techniques and the development of reliable flaps for reconstruction. The concept of maintaining quality of life has become particularly important in the overall care and treatment of cancer patients. Thus, even patients with a very limited life expectancy are routinely reconstructed if it is expected that their quality of remaining life would be significantly enhanced. The high success rate of head and neck reconstructive procedures has allowed for significant improvement in both functional and aesthetic results and has completely changed the conceptual approach to mandibular reconstruction. Only patients who are medically unfit to tolerate a long operation or have a grave prognosis are excluded as candidates for resection and immediate reconstruction.

Repair of the mandibular defect most commonly includes bone as well as soft tissue with which to replace either intraoral lining, external skin or both. It is also desirable that skin used to reconstruct the inside of the mouth be innervated.

The choice of reconstruction depends on factors such as the bone and soft tissue requirements and the site of the defect. Donor site availability and morbidity, ease of flap dissection and status of the recipient vessels in the neck as well as the patient's overall medical condition may also influence the final decision. However, while microsurgery has revolutionized mandibular reconstruction, there is still also a place for more traditional techniques. Smaller defects can sometimes be reconstructed with reconstruction plates alone, and in certain circumstances the use of nonvascularized bone is still a reasonable approach. It may even be acceptable not to reconstruct the bony defect in a small subset of patients. There is one absolute indication for vascularized bony mandibular reconstruction. That is in the central anterior mandibular defect. Using any other technique results in an unacceptable functional and cosmetic result. Many different flaps have been used for mandibular reconstruction. While the iliac crest still has a place and the radial forearm and scapiular flaps have their proponents, the fibular flap has emerged as the gold standard.

The Fibular Osseocutaneous Free Flap

The fibula can provide up to 25 cm of uniform shaped bicortical bone. It can tolerate multiple osteotomies because of its profuse periosteal blood supply. The bone stock is adequate to support osseointegrated implants, however the height of the neomandible is limited relative to that of the native dentate mandible. The skin island, based on the septocutaneous blood supply is adequate in size and reliable. The skin has the potential for innervation but its quality is intermediate in thickness and pliability and therefore ranks behind that of the radial forearm flap. The vascular pedicle is adequate in length and can be effectively lengthened by dissecting it off the proximal fibula. The flap can include the flexor hallucis longus muscle to provide soft-tissue bulk where needed. A two team approach allowing simultaneous ablation and flap harvest is perfectly feasible with the fibula.

The Iliac Crest Osseocutaneous Flap

The ileum, based on the deep circumflex iliac artery (DCIA) and vein has a natural curvature not unlike that of the mandible. A total of 14-16 cm of bone can be harvested by extending the resection posteriorly to the sacro-iliac joint. This bone can be contoured to reconstruct the anterior mandibular arch with osteotomies through the outer cortex and it is well suited for placement of osseointegrated implants. The blood supply of the skin paddle of the osseocutaneous flap comes from an array of perforators that are located in a zone along the medial aspect of the iliac crest. It is important when insetting the skin paddle to maintain the relationship of skin to bone so as not to torque these perforators. Furthermore, the skin is bulky and not particularly pliable so that it is usually less than the optimal choice for intraoral reconstruction. Donor site morbidity can also be substantial. Patients are frequently slow to mobilize because of pain on walking. Moreover, abdominal wall weakness, frank herniation and occasional gait disturbances can occur. The donor defect of the DCIA can be minimized by splitting the ileum and taking only the inner table of the bone with the flap. In this manner, the crest itself is left and the abdominal repair is much more secure. Holes are drilled in the remaining crest to which the three layers of abdominal musculature are attached. Furthermore, the muscles on the lateral side of the crest are undisturbed, further minimizing donor morbidity. Finally, the cosmetic defect of this maneuver is significantly less than when the traditional flap is used. The only disadvantage to this technique is that the thickness of bone harvested by this means is generally inadequate to facilitate use of osseointegrated implants for dental rehabilitation. One other modification is to harvest internal oblique with the flap rather than skin. This provides ample quantity of healthy muscle which can then be used to reconstruct the soft tissue portion of the defect.

The Scapular Osseocutaneous Flap

Based on the circumflex scapular artery, this flap has the advantage of providing an extensive expanse of skin as well as bone. Furthermore the skin can be taken as separate skin paddles, a scapular as well as a parascapular flap based on the transverse and descending branches of the circumflex scapular artery respectively. The bony perforators, which are direct short branches from the circumflex scapular artery, supply the lateral border of the scapula and provide approximately 8 cm of good bone stock. Medial scapula can also be harvested with this flap but harvesting lateral bone is more usual. Because of the anatomical characteristics of the vascular pedicle, the various elements of this flap (two skin paddles and bone) can all be manipulated independent of one another as there is sufficient vascular length to facilitate this. This makes it very versatile for reconstructing complex three dimensional defects. However it has the disadvantage that the patient has to be turned in order to harvest this flap.

The Radial Forearm Osseocutaneous Flap

The radial forearm flap provides probably the best quality skin for intraoral reconstruction. It is soft, thin, pliable and can be harvested with the lateral antebrachial cutaneous nerve making it an innervated flap. The quality of this re-innervation has been well documented. The radius itself provides a thin strip of bone which nevertheless is very strong and despite its size can tolerate osseointegrated dental implants. When harvesting the bone it is important to limit this harvest to approximately 30% of the circumference of the radius and to shape this harvest in the shape of a keel to minimize the risk of fracture of the residual radius. Despite these precautions the incidence of fracture is reported as 15% which is very high considering that up to half of these patients will require a secondary surgical procedure to fix the radial fracture.

The Resection

Replacing resected mandible with a replica of what has been removed is important. There are several ways in which this can be done. Probably the commonest and simplest method is to apply the reconstruction plate which will ultimately be used for fixation to the mandible before resection. This ensures that when the plate is replaced, the remaining elements of the mandible will be in exactly the same relative position as they were preoperatively. Thus, optimal occlusion as well as undisturbed temporomandibular joint dynamics can be assured. The plate is therefore applied to the mandible, the holes are drilled and screws applied. The plate is then removed and used as a template for shaping the bony reconstruction, whichever flap is chosen for that purpose.

In through and through lesions where the outer cortex of the mandible is involved this technique cannot be used as the reconstruction plate cannot be applied to the mandible prior to resection. One way around this problem is to make a template of the mandible preoperatively from the preoperative CT scans. This template can then be sterilized and used to shape the reconstructive plate intraoperatively. Alternatively, the mandibular elements can be stabilized prior to resection of the bone. This is done by applying a bridging bar to the mandible. Once the mandible has been resected the reconstruction plate can be bent to the shape of the mandible knowing that the remaining elements are once again held in the same relative position as preoperatively, again maintaining occlusion and TMJ dynamics.

Summary

Head and neck reconstruction is a complex field. There are several workhorse flaps which are routinely used to reconstruct specific defects. The surgeon should be familiar with many different techniques so that the specific reconstructive requirements for each individual patient can be met.

Microsurgery in Lymphatics

Corradino Campisi

General Clinical Aspects

Among peripheral lymphatic disorders, lymphedema represents a pathology with a relatively significant incidence worldwide. Lymphedema, from the etiopathogenetic point of view can be divided as primary or secondary.

Primary lymphedema, also called idiopathic, has no clearly recognizable etiology, although triggering etiological factors can frequently be found. Lymphedemas with onset at birth (congenital) are included in this category and sometimes are hereditary-familial (Nonne-Milroy's disease), often associated with chromosomal abnormalities. Primary lymphedemas, depending on the time of their appearance, may have early or late onset, which can be triggered by little traumas, infections or surgery. Above all in females, predisposing factors are to be identified in alterations of their neurohormonal status (neuroendocrine lymphedemas). Primary lymphedemas can be related to general conditions of lymphatic and/or lymphnodal dysplasia, hypoplasia or hyperplasia (with increased lymph production). Lymph nodes and/or lymphatics can be involved in abnormal lymph outflow.[3,4] In most cases of hypoplasia, however, lymph node involvement can almost constantly be demonstrated and leads to the progressive secondary alteration of lymphatic vessels. From pathophysiologic and diagnostic points of view, this picture is practically the same as secondary lymphedemas resulting from lymphadenectomy and/or radiotherapy. About 90% of all primary lymphedemas are characterized by hypoplasia or dysplasia of the lymph nodes and/or lymphatics. In primary lymphedemas, hypoplasia and dysplasia result in diminished ability to form and activate a proper collateral circulation in those cases in which it is essential, such as traumas, infections and surgery. In about 8-10% of primary lymphedemas a condition of increased number and size of lymphatic collectors can be found, associated with structural lymphatic and lymph nodal dysplasia. Also disorders in lymphogenesis play an important role from a lymphodynamic point of view. A condition of hyperlymphogenesis may derive from preexisting regional arteriolo-venous hyperstomies, arterial-venous fistulas (i.e., in Klippel-Trénaunay's disease) or related angiodysplasia. Conditions of reduced or absent production of lymph, as well as agenesis, hypoplasia, or impaired permeability of initial lymphatics, conversely, are very rare. Finally, among lymphodynamic abnormalities, apart from insufficient lymph drainage along anatomically pre-established pathways, gravitational lymph and/or chylous reflux pathologies should be mentioned. The top-to-bottom lymph backflow is caused by insufficient antigravitational structures, normally represented by valves, the reticu-

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lar myoelastic layer of lymphatic walls, and lymph nodal architecture (lymphedemas and chyledemas due to gravitational reflux).

In secondary lymphedemas (called also acquired), the etiology can be clearly identified on history and physical examination. It is possible, therefore, to distinguish posttraumatic, postinfection, postinflammation (postlymphangitic, postphlebitic) lymphedemas, and those caused by radiotherapy, surgery, paralysis, neoplasm, and parasites. Lymphatic filariasis is endemic in some tropical and subtropical areas in Asia, Africa, and Latin America. However, also secondary lymphedemas often have some congenital predisposition. For instance, arm lymphedema secondary to breast carcinoma treatment, that occurs in 5-35% of cases also depending on whether surgery is associated with radiation therapy, is known to be more likely to occur when there is no deltoid pathway. This lymphatic pathway drains the lymph coming from the arm directly into the supraclavicular lymph nodes, skipping the axillary stations. With preventive lymphoscintigraphic studies, comparing the arm ipsilateral to the breast cancer site with the contralateral one, patients with a higher risk of developing secondary lymphedema can be identified and should, therefore, receive preventive therapeutic treatment. Predisposing factors for congenital wall-valve dysplasia of the lymphatics are always found even in lymphatic filariasis. Based on these data, therefore, Tosatti's classification of lymphedemas proposed more than 30 years ago seems to be still valid.

Apart from some exceptional cases of acute postlymphangitis and/or posttraumatic types, lymphedema is normally a chronic, progressing, ingravescent, and disabling condition characterized by the progressive volume increase of the limb(s) involved, up to elephantiasis, with severe functional impairment. This disease, which evolves by phases, is characterized by frequent acute lymphangitic, erysipeloid, recurrent complications with subsequent severe septic conditions, dermatoliposclerotic indurated cellulitis, chronic fibrosclerotic lymphoadenitis (in primary lymphedemas), and lymphostatic warmth. The degeneration into lymphangiosarcoma (Stewart-Treves syndrome) is a rare sequel, more likely to occur in postmastectomy lymphedemas, not to be confused with local cutaneous recurrence of breast cancer. Sometimes, lymphedema can be associated, especially when involving the lower estremity, with Kaposi's sarcoma, the latter not necessarily caused by HIV-related acquired immunodeficiency syndrome.

Lymphatic Assessment

Based on medical history and objective examination, the time and conditions of onset, location, evolution, and extent, volume, and semiological features of lymphedema can be assessed and a differential diagnosis from phlebedema can be made. Lymphedema is hard to the touch, while venous edema is soft and has the typical fovea sign under finger compression. This difference above all depends on the stagnant lymph being an excellent pabulum for fibroblasts in the subcutaneous connective tissue, that mature more rapidly into fibrocytes, thus forming fibrosclerotic connective tissue. Lymphedema has a typically rhizomelic or columnar location, whereas the venous edema has an acromelic arrangement, except for phlegmasia dolens, caused by acute deep thrombophlebitis of the femoral-iliac region. Unlike phlebedema, lymphedema does not usually evolve into dystrophic-dyschromic skin lesions and ulcers. It is more likely to be complicated by acute reticular erysipeloid lymphangitis, caused by gram-positive cocci infections promoted by lymph stasis. Phlebedema is often associated with varices and varicophlebitis, and unlike lymphedema, especially in the morning, it is subject to rapid postural changes and is characterized by abnormal Doppler venous flow rates with significant venous pressure increase when the patient is in clinostatic and orthostatic position. However, mixed types (like in stage III postphlebitic syndrome) of lymphophlebedema or phlebolymphedema also exist, with prevalence of either venous or lymphatic component. The much more complex picture of angiodysplasia characterized by a condition of arteriolo-venous hyperstomy (i.e., Mayall's syndrome), or by congenital arterial-venous macro- and microfistulas (e.g., Klippel-Trénaunay's disease) is also to be included in these mixed forms. Gigantism with elongation of the affected limb and more or less severe foot dysmorphism, flat and map-like "Port wine" color angioma, with hyperhidrosis of the plantar surface, are all typical signs of the latter pathology. There are also some spurious forms, masked by prevailing lymphedema and therefore more difficult to recognize. In these cases, arterial-venous circulation investigations and, particularly, Doppler venous pressure measuring may not be helpful enough, and further instrumental investigations may be required: phleboscintigraphy, phlebography, and digital arteriography, when angiodysplasia is suspected.

For the time being, lymphangioscintigraphy and conventional oil contrast lymphography are the most suitable investigations of lymphatic and chylous edemas. Lymphangioscintigraphy[1] is the most popular method used for the screening of lymphedemas. Since it is a noninvasive method, it can be easily repeated in the patient follow-up, especially after microsurgery. A small tracer dose (Tc^{99m}) adsorbed in colloid spherules (colloid sulphide, rhenium, dextran) is injected in the dermis-hypodermis, in the interdigital spaces. The lymphotropic nature of these substances permits display of the preferential lymphatic pathways with a gamma-camera and allows measurement of the flow rate and lymph node uptake. A tracer clearance measurement is a very useful parameter from a lymphodynamic point of view. Direct lymphangiography is better indicated in the study of gravitational reflux lymphatic and chylous edema of the lower limb and external genitalia when requiring a surgical treatment. In this examination, ultrafluid "Lipiodol" is injected into a lymphatic collector, preferably isolated with microsurgical technique, of the dorsum of both feet. This type of investigation is minimally invasive and some, although rare, general (e.g., pulmonary microembolism, in case of peripheral lympho-venous fistulas, allergy to contrast medium) and local (e.g., infection on the site of skin incision, acute lymphangitis, lymphorrhea) complications may occur. If performed, however, according to well-established standards, direct lymphography has no statistically significant sequelae. This investigative method can also be performed in children. It enables a morpho-functional study of the superficial and, with the use of proper technical artifices, also deep circulation. Lymphangioscintigraphy is the examination of choice, while lymphangiography should be reserved for cases of gravitational reflux lymphedema and chyledema with doubtful interpretation and more likely to be treated surgically. Also CT, ultrasonography, and the recent lymphangio-magnetic resonance imaging preoperatively offer important data on lymphatic and chylous dysfunction. Indirect lymphangiography performed with dermo-hypodermic injection of a water-soluble contrast medium ("Iotasul") is useful to clarify some etiopathological aspects of primary lymphedemas. Also fluorescent microlymphography, thanks to recent studies by Allegra et al, demonstrates important parameters in assessing the status of the superficial dermis lymphatic web, which reflects the functional condition of peripheral lymphatic circulation. The conventional Houdack-McMaster dye test with the injection of highly lymphotropic vital stain (Patent Blue V) is used today as a preliminary investigation in direct lymphangiography and microsurgery for a better and faster assessment of lymphatics. Recent studies by Olszewski[2] and Bryla and Campisi et al have developed a system to measure endolymphatic pressure and lymphatic flow rate. These parameters, together with venous pressure assessment, help measure the lymph-venous pressure gradient that is essential for a correct approach to microsurgical treatment of lymphedemas. A lymphatic vessel is isolated and cannulated at the lower third of the leg medial surface. With this method, which can be performed during microsurgery, any changes in the flow-pressure rate can be recorded in clino- and orthostatic position, at rest and under dynamic conditions. These studies have shown that a valuable lymphatic-venous pressure gradient is essential to obtain medium- and long-term results by derivative microsurgery.

Nonoperative Treatment

Owing to the physiopathological and clinical investigations, particularly of Földi,[3] the foundations were laid for a conservative medical-physical treatment, with the development of the manual lymphatic drainage, clinically codified by Vodder, Foldi, and Leduc. Even compression therapy with the use of special devices available in different models (air, mercury compression) has been improved and gradually propagated. The specific medical treatment includes the use of antibiotics, long-acting penicillin in particular, according to long-term protocols recommended by Olszewski, anti-inflammation drugs, associated with the essential hygienic measures and the constant use of suitable bandages and elastic compression garments. The positive effect of benzopyrones was described above all by Casley-Smith, but their correct use for the treatment of lymphedemas has not yet been clearly elucidated. As concerns thermotherapy, from the use of ovens in ancient China, hot-wet compress in the Latin-Mediterranean world, we passed to microwaves proposed by Chang and hydrothermotherapy (hot-wet air in a closed circuit) by Campisi et al, used for the treatment of postlymphangitis lymphedemas.

Operative Treatment

At the end of the ’60s, there were very few therapeutic solutions to the treatment of lymphedema. Only the most severe and advanced cases of elephantiasis were surgically treated, mainly in order to reduce the volume of lymphedematous limbs. The most popular surgical methods were those according to Charles (total resection of skin-lipid layers), Thompson (drainage with scarred subfascial skin flap), and Servelle (total surface lymphangectomy). Being highly destructive and invasive operations, they could not be recommended in less advanced or initial stages and even less so in children. Thus, for those patients resistant to conservative treatment, new and more suitable surgical solutions, aiming at correcting the mechanisms of lymphedema, that could shorten the duration of the disease, spare the patients frequent and long hospitalization, and allow them to go back to their family and work, were sought. As early as the '70s, Tosatti[4] proposed a method of antigravitational ligation of dilated and insufficient lymphatics for the treatment of the lower extremities and external genitalia due to gravitational reflux. This method is one of the first models of functional, direct surgical approach to lymphatics and lymph nodes. The advent of microsurgery has given an outstanding contribution to this new approach.[5] Lymphnodal-venous and multiple lymphatic-venous anastomosis came to the fore. At the same time, based on more clinical experience and improved surgical equipment and techniques, greater knowledge was gained of lymphangiology and the results of lymphatic microsurgery. These methods are beneficial not only to secondary, but also primary lymphedemas, since early intervention is possible even in young children with some adequate modifications of techniques such as lymphatic-capsule-venous anastomosis.[6] In the great majority of primary lymphedemas, especially of the lower extremities, histopathologic lymph node alterations exist (pulpal fibrosclerosis, with dilatation of afferent lymphatics and leiomuscular wall hyperplasia), which characterize the obstructive nature of this type of lymphedema, similar to secondary ones. Therefore, derivative lymphatic microsurgery is typically expressed in multiple lymphatic-venous anastomosis[7] (Fig. 14.1). For cases where lymphostatic disease is associated also with venous impairment, (from venous hypertension to varices, from acute surface and/or deep thrombophlebitis to postphlebitic sequelae), which are a contraindication to derivative lymphatic-venous surgery, reconstructive lymphatic surgery techniques have more recently been developed. It is thus possible to obtain long-term satisfactory results with the use of segmental autotransplantation of lymphatic collectors, which can be performed only for the treatment of monolateral lymphedema. Furthermore, interposition autologous venous grafting or lymphatic-venous-lymphatic plasty[8] (Fig. 14.2) can be employed. With this technique, that is easier and faster than the previous one, bilateral lymphedemas also can be treated. A direct end-to-end anastomosis between the lymphatic collectors upstream and downstream the obstruction, as an alternative solution to the venous or lymphatic graft, can be performed only very rarely, especially in secondary lymphedemas. The use of free microvascular lymphatic or lymph nodal flaps is still under clinical testing. However, it opens up very interesting prospects regarding the treatment of lymphedemas which fail to respond to a correct conservative medical therapy and which, for congenital (aplasia or hypoplasia) or acquired (elephantiasis with diffuse obstructive lymphangitis) reasons, cannot benefit from the above mentioned derivative or reconstructive microsurgical techniques. With a follow-up at 1, 3, 6 and 12 months and once a year for the first 5 years after surgery, positive results from lymphatic microsurgery can be achieved in all patients (Figs. 14.3-14.5), with best results among patients who have undergone operations at stage II or III.[9] Comparative measurements of the circumferences of the various segments of the lymphedematous limb, volumetric studies, and lymphangioscintigraphy are essential to demonstrate the efficacy of derivative and reconstructive microsurgery (Fig. 14.6).

Final Remarks and Future Applications

In the complex therapy for lymphedemas, the role to be played by surgery versus medical-physical conservative treatment can be easily defined.[10] Combined physiotherapy is the treatment of choice for most lymphedemas. In nonresponsive cases

Fig. 14.1. Multiple lymphatic-venous anastomoses performed by microsurgical technique, using the operating microscope at 30x magnification.

(up to 30-40%), the drainage function of the lymphatic circulation can, at least partially, can be recovered by lymphatic microsurgery performed as early as possible. The rather constant outcome can further be improved with subsequent conservative treatment. Major resective surgery is no longer justified. Only in rare cases, as soon as the results of microsurgical and medical conservative treatment have become stable, does minor resective surgery still find some indications for aesthetic-reductive purposes.

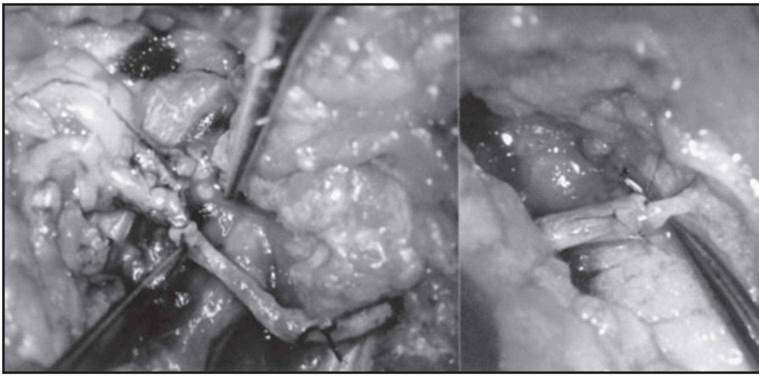

Fig. 14.2. Lymphatic-venous-lymphatic interpositioned vein graft carried out by means of the operating microscope (25x): a) distal anastomoses and b) proximal anastomoses, below and above the inguinal region.

Fig. 14.3. Primary leg lymphedema (a) in pediatrics. Microsurgical derivative lymphatic-venous drainage was performed at the inguino-crural region. Microsurgery allowed to obtain a rapid reduction of the edema at both sides (b).

With regard to prevention of secondary lymphedemas, finally, early diagnosis plays an important role as well as the selection of high-risk patients for the onset of lymphostatic disease after oncological lymphadenectomies, especially if associated with radiotherapy. In these cases, early microsurgery is a valid suggestion in order to treat, from their very onset, lymphedemas which, based on a reasonable statistical probability, are expected to show unrelenting progression.

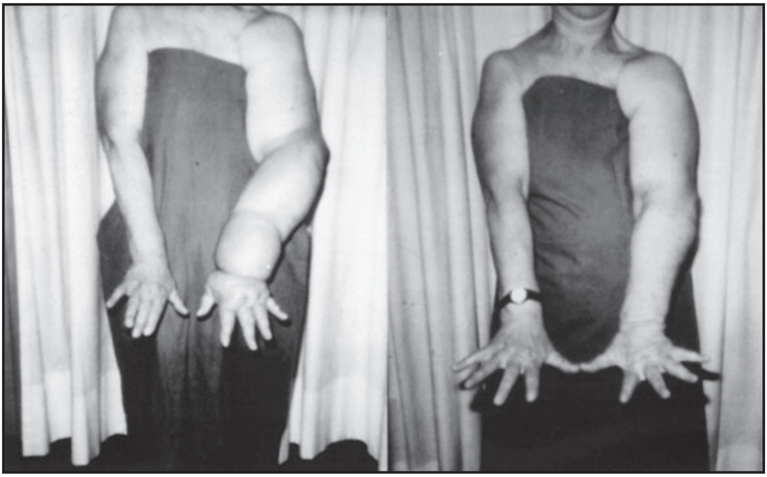

Fig. 14.4. Left arm lymphedema (a) secondary to breast cancer treatment. Lymphatic-venous microsurgical anastomoses at the arm allowed to achieve a very good result, stable with time, controlled at over 5 years (b).

Fig. 14.5a. Primary right leg lymphedema.

Fig. 14.5b. Primary right leg lymphedema, treated by derivative lymphatic-venous microsurgery, and controlled at long distance of time from operation.

Based upon over 25 years clinical experience, we can conclude by emphasizing the efficacy of microsurgery for the treatment not only of patients with acquired lymphedema, but also with primary lymphostatic pathology, even in pediatrics, and moreover for the prevention of secondary lymphedema.

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Fig. 14.6. Lymphoscintigraphic demonstration of the patency of lymphatic-venous anastomoses at the arm, performed over 10 years before for the treatment of secondary arm lymphedema.

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