Nerve Grafts and Conduits

16

Larry M. Wolford and Daniel B. Rodrigues

Injuries to the peripheral nervous system affect 1 in 1,000 individuals each year. The implications of sustaining such an injury are considerable, with loss of sensory and/or motor function [34]. Some nerve injuries require repair in order to regain sensory or motor function. Although this chapter focuses primarily on trigeminal nerve (TN) injuries and repairs, the facts presented may apply to any peripheral nerve repair. The primary indications for nerve repair or grafting include the following: (1) an injury or continuity defect in a nerve, as a result of trauma, pathology, surgery, or disease, which cannot regain normal function without surgical intervention, and (2) loss of normal neurologic function, resulting in anesthesia, paresthesia, dysesthesia, or paralysis, which cannot be corrected by nonsurgical treatment. In some nerve injuries (e.g., neuropraxia), the nerve regains sensory or motor function unless irreversible compression, neuroma (axonotmesis), or transection (neurotmesis) occurs. In more severe injuries, there may be significant loss of nerve substance (continuity defect), or a section of nerve may need to be removed to expose normal nerve tissue in preparation for nerve repair. Thus, nerve repair and nerve grafting procedures may be required to provide continuity between the proximal and distal portions of the nerve.

The three major branches of the TN that can be involved in injuries are the inferior alveolar nerve (IAN), lingual nerve (LN), and infraorbital nerve (ION). The most common types of injury to the IAN and LN are iatrogenic, related to removal of impacted teeth (Fig. 16.1), orthognathic surgery (Fig. 16.2a, b), periodontics, endodontics (Fig. 16.3), dental implants (Fig. 16.4), curettage

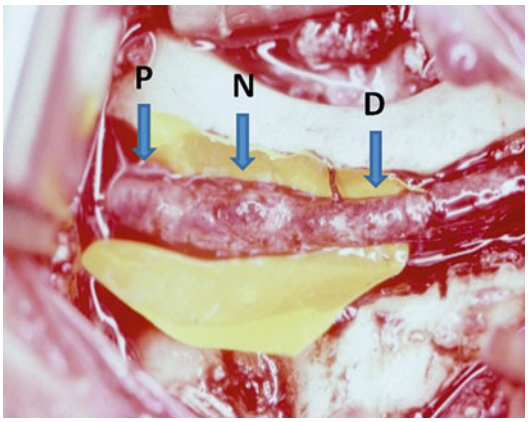

Fig. 16.1 A large traumatic neuroma (*N*) is seen 1 year after removal of a third molar. Note the significant atrophy of the distal (*D*) portion of the nerve and the mismatch in size compared with the proximal (*P*) portion of the nerve

L.M. Wolford, DMD (✉)
Department of Oral and Maxillofacial Surgery,
Texas A&M University Health Science Center,
Baylor College of Dentistry,
Private Practice at Baylor University Medical Center,
3409 Worth Street – Suite 400, Dallas,
TX 75246, USA
e-mail: lwolford@swbell.net

D.B. Rodrigues, DDS
Department of Oral and Maxillofacial Surgery,
Universidade Federal da Bahia/Obras Sociais
Irma Dulce and Private Practice,
Avenida ACM n 3244 sala 917. Caminho das Arvores,
Salvador, BA CEP 41800-700, Brazil
e-mail: dbarrosr@yahoo.com.br

M. Miloro (ed.), *Trigeminal Nerve Injuries*,
DOI 10.1007/978-3-642-35539-4_16,

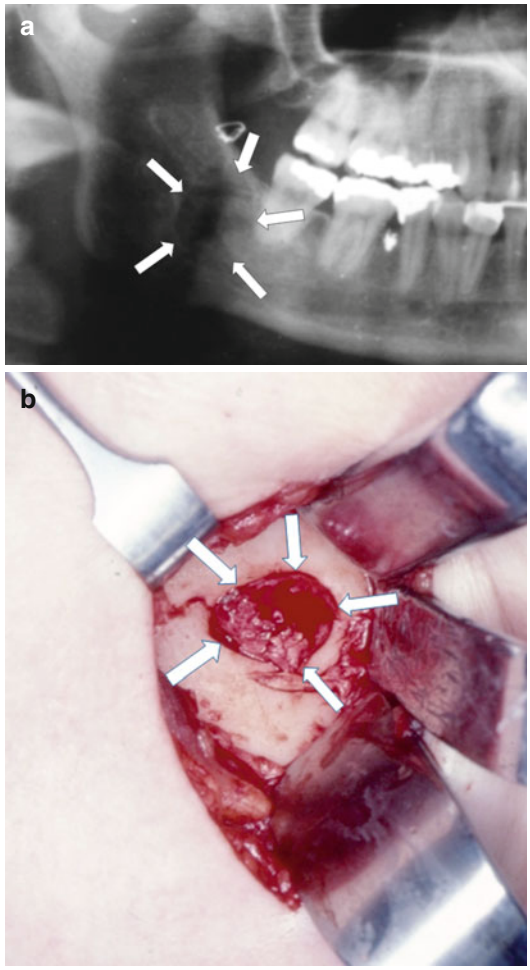

Fig. 16.2 (**a**) A posteriorly directed lateral osteotomy for a sagittal split procedure injured the IAN causing a large neuroma that created a bone defect in the buccal cortical plate (*arrows* outline bone defect). (**b**) The neuroma (outlined by *arrows*) is observed through an extraoral approach

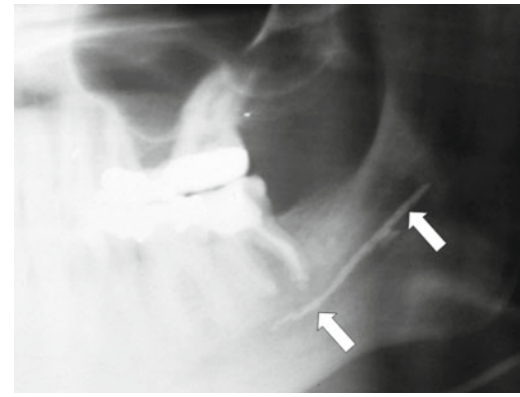

Fig. 16.3 A root canal procedure was performed on a mandibular molar with Sargenti paste injected into the root canals with extravasation (*arrows*) into the IAN canal. This caustic material causes severe nerve damage that adversely affects the nerve beyond the extent of the material

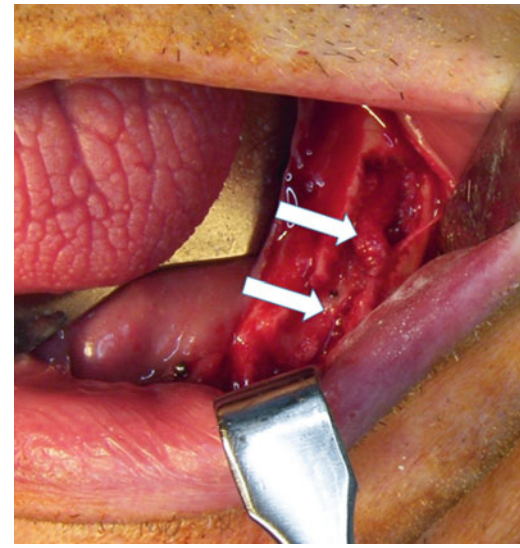

Fig. 16.4 This nerve injury resulted from placement of a dental implant that crushed the IAN. The injured IAN is between the *arrows*. Note the atrophy of the distal nerve segment

of intrabony lesions, partial or total resection of the mandible or tongue in tumor removal, and other surgical procedures as well as trauma. Injuries to the ION are more commonly caused by trauma to the middle third of the face (Fig. 16.5a), partial or total maxillectomy and orbital exenteration during resection of benign or malignant tumors, or inadvertent nerve injury during maxillary and midface osteotomy procedures. Nerve injuries which are more difficult to manage include severe stretch-type injuries and chemical injuries such as those that occur when alcohol, steroid, or other caustic agents are injected into or around nerves (Fig. 16.3). The nature and extent of the nerve pathology will influence the type and quality of repair [54, 55].

16.1 Considerations for Direct Nerve Repair

When surgical repair is required for a transected nerve or a nerve injury requiring excision, the best results, when conditions permit, are achieved

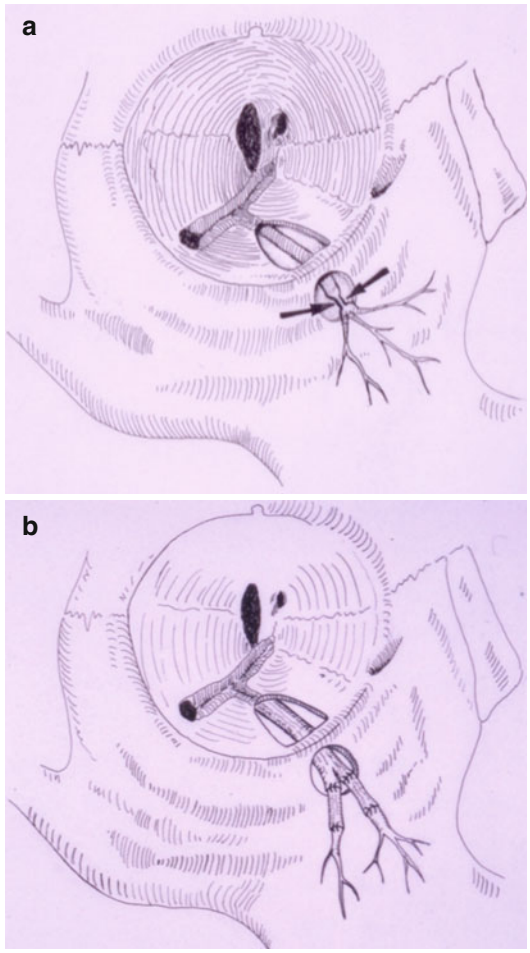

Fig. 16.5 (**a**) This illustration shows a crush injury to a right infraorbital nerve from a previous zygomatico-orbital fracture. (**b**) The nerve has been repaired with nerve grafts obtained from the greater auricular nerve as a cable graft

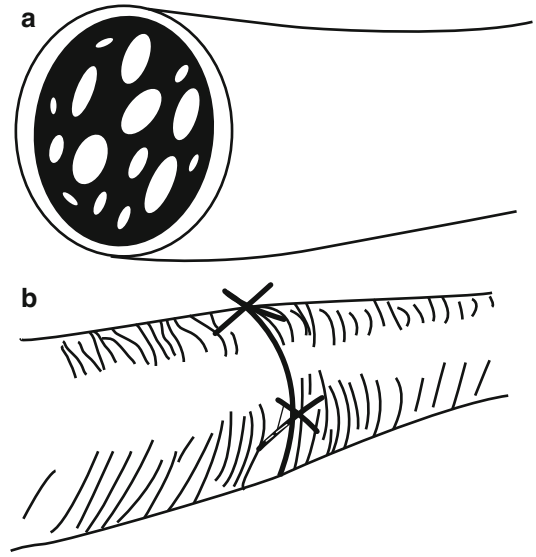

Fig. 16.6 (**a**) Since the trigeminal nerve is polyfascicular and the fascicles are non-grouped, (**b**) the epineurial repair is the preferred technique for neurorrhaphy

with a direct nerve repair, without grafting. There are basically three types of nerve repair.

Perineural repair involves repairing the individual fascicles and placing sutures through the perineurium. Complications of this technique include trauma to the nerve in dissecting out each fascicle and fibrosis that develops because of the dissections and numerous sutures placed. The IAN and LN may have 9–21 fascicles depending on the location of the injury, so this perineurial repair method is impractical.

Group funicular repair involves repairing grouped fascicles with sutures placed through the intraneural epineurium, aligning groups of fascicles. Since the TN branches have non-grouped fascicles, this technique is not applicable.

Epineurial repair involves aligning the nerve ends and placing sutures through the epineurium only. Since the TN branches are polyfascicular (multiple, different-sized fascicles) and non-grouped, the epineurial technique is the most logical choice of repair method for the TN (Fig. 16.6a, b).

16.2 Considerations for Autogenous Nerve Grafts

When continuity defects are present in the injured nerve or created in preparation of nerve repair, a nerve graft procedure may be indicated. An additional indication includes nerve sharing, where the proximal end of a nerve is severely damaged and nonfunctional, but the distal aspect can be salvaged. A portion of another nerve is isolated, a nerve graft attached, and anastomosed to the distal end of the injured nerve (Fig. 16.7a–c). There are various types of donor nerve grafts available including the following: *Autogenous nerve graft* is transplanted from one site to another in the same recipient; *isograft* is transplanted between genetically identical and nearly identical

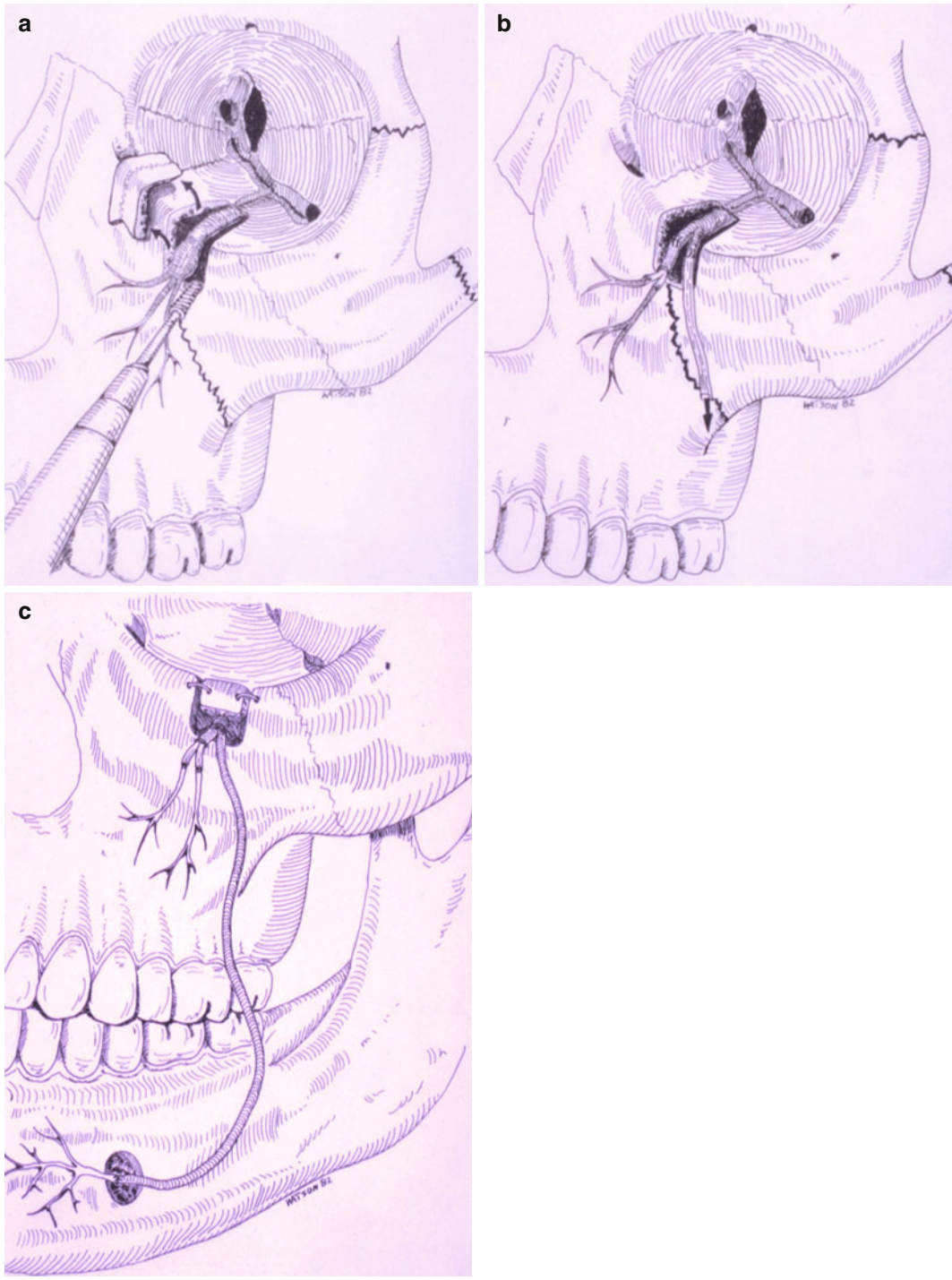

Fig. 16.7 (**a**) Diagram showing injury to the infraorbital nerve and loss of the proximal branch of the IAN from severe facial trauma, but the mental nerve was still present. (**b**) The infraorbital nerve was divided with short sural nerve grafts used to reanastomose the distal branches of the infraorbital nerve and a long graft from the other part of the proximal infraorbital nerve and (**c**) to anastomose to the mental nerve. In this case of nerve sharing or nerve transfer, the patient did regain some sensibility to the distribution of these nerve branches

individuals; *allograft* is transplanted between genetically nonidentical individuals of the same species; and x*enograft* is transplanted from a donor of one species and grafted into a recipient of another species.

The two most common autogenous donor nerves for TN repair are the sural and the greater auricular nerves. Selection of a donor nerve is predicated in part on ease of harvesting and on minimizing postsurgical symptoms associated with the donor nerve and its functional distribution. Both the sural and greater auricular nerves are relatively easy to harvest but yield localized areas of sensory deficit after surgery. Other potential donor nerves include the saphenous dorsal cutaneous branch of the ulnar nerve, the medial antebrachial cutaneous, lateral antebrachial cutaneous, superficial branch of the radial, intercostal, and other nerve branches of the cervical plexus [24, 47]. Several factors that are important to consider when selecting a donor nerve are as follows.

16.2.1 Diameters of Donor and Host Nerves

Ideally, the diameter of the nerve graft should correlate exactly with the diameter of the proximal and distal ends of the prepared host nerve. The average diameter of the IAN is 2.4 mm [43]; LN, 3.2 mm [1]; sural nerve, 2.1 mm [8]; and greater auricular nerve, 1.5 mm [43]. For IAN grafting, the sural nerve is generally considered the best cross-sectional match because its diameter is 87 % that of the IAN, but only 66 % that of the LN. The greater auricular nerve diameter is about 63 % of the IAN and 47 % of the LN diameter. The greater auricular nerve works best if placed as a cable graft (Fig. 16.8), with two or more parallel graft strands, so the combined diameter of the two strands would be adequate (125 % of the IAN and 94 % of the LN diameter).

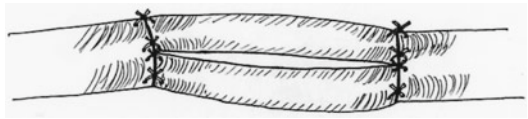

Fig. 16.8 The cable grafting technique may be indicated to improve the match of graft to host nerve in cross-sectional diameter, number of fascicles, and fascicular pattern

16.2.2 Length of Nerve Graft Required

It may be difficult to obtain a graft longer than 2–4 cm from the greater auricular nerve. Since the greater auricular nerve (Fig. 16.9a) is generally half the diameter of the IAN and LN, a two-strand cable graft usually works best for diameter match (Fig. 16.8). Therefore, it may be difficult to graft a defect larger than 1–1.5 cm if the graft is harvested unilaterally. The sural nerve is larger in diameter, and a 20- to 30-cm length can be harvested without much difficulty (Fig. 16.9b). Since a longer graft will usually be necessary for nerve sharing techniques, the sural nerve would be the autogenous donor choice (Fig. 16.7a, b).

16.2.3 Number of Fascicles

The number and size of fascicles should correlate between the donor and host nerves. The IAN usually has 18–21 fascicles in the third molar area (Fig. 16.10a), decreasing to about 12 fascicles just

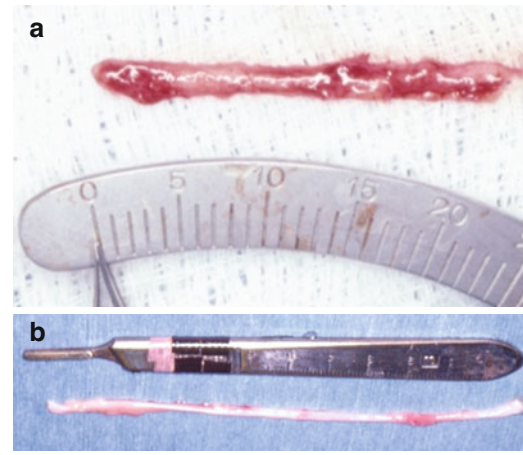

Fig. 16.9 (**a**) The greater auricular nerve provides a shorter length of graft, and the diameter is significantly smaller than the trigeminal nerve branches. (**b**) A significantly longer graft can be harvested from the sural nerve, and it has a larger diameter than the greater auricular nerve

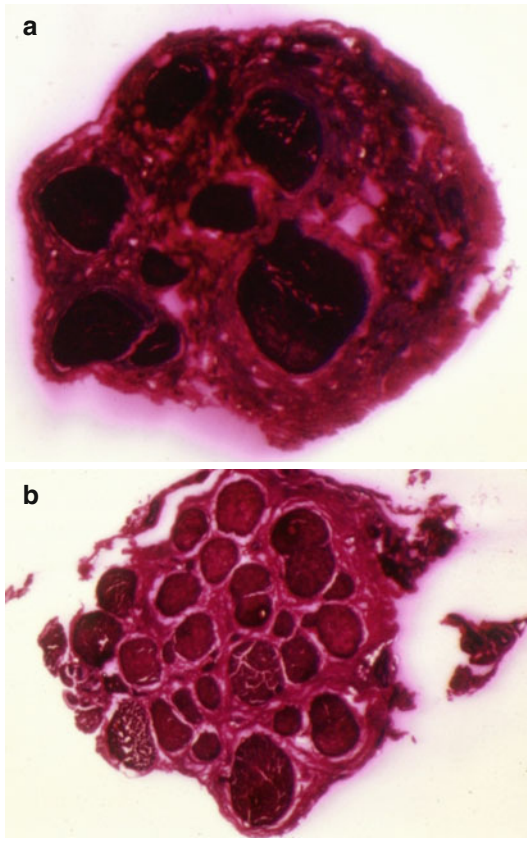

Fig. 16.10 (**a**) This cross-sectional histological view of the IAN at the third molar area shows the polyfascicular pattern. (**b**) Just proximal to the mental foramen, the number of fascicles in the IAN decreases significantly

proximal to the mental foramen area (Fig. 16.10b) [43]. The LN in the third molar area usually has 15–18 fascicles [1], decreasing to 9 fascicles as it enters the tongue [48]. The sural nerve usually has 11–12 fascicles [8], which is 54 % of the number of fascicles in the IAN and 69 % of the number in the LN. The greater auricular nerve usually has 8–9 fascicles [47], which is significantly less than the number in the IAN (44 %) and LN (52 %). However, if a cable graft with two parallel nerve graft strands is used (Fig. 16.8), the combined number of fascicles correlates more closely with those of the IAN (87 %) and LN (104 %). Sometimes, the greater auricular nerve is even smaller, and the transverse cervical nerve may be considered. If the nerve graft is significantly smaller in diameter than the proximal host nerve stump, useful fascicles are lost, and a neuroma may form from collateral axonal microsprouting. If the graft is too large at the distal host nerve stump, then some of the regenerating nerve fascicles in the graft will be lost. If the distal portion of the graft is smaller than the distal portion of the host nerve, then a number of the fascicles in the distal portion of the host nerve will not regenerate.

16.2.4 Fascicular Pattern

The IAN and LN have polyfascicular patterns; the fascicles have various sizes from small to large diameter, but without fascicular grouping [1, 43]. The sural nerve has an oligofascicular (uniform size) pattern, but with small-diameter fascicles [8]. The greater auricular nerve is a polyfascicular nerve with grouping, a pattern that more closely approximates the fascicular pattern of the IAN and LN than the sural nerve [44]. The axons in the sural nerve are much smaller and fewer in number than those in the IAN and LN, creating another significant mismatch.

16.2.5 Cross-Sectional Shape and Area

The IAN and LN are round [1, 43], whereas the sural nerve is basically flat or elliptical. The greater auricular nerve is round-oval, and therefore, it more closely resembles the IAN and LN than does the sural nerve. The approximate total cross-sectional area of the IAN is 4.6 mm^2; the LN, 5.2 mm^2; the sural nerve, 3.5 mm^2; and the greater auricular nerve, 1.8 mm^2. There is no significant difference in fascicular pattern and total nerve areas among the IAN, LN, and greater auricular nerve [1, 43]. The sural nerve has significantly smaller axonal size and number of axons per unit area (50 % less) than the others [16].

16.2.6 Patient Preference

Harvesting the sural nerve results in numbness of the heel and lateral aspect of the foot (Fig. 16.11).

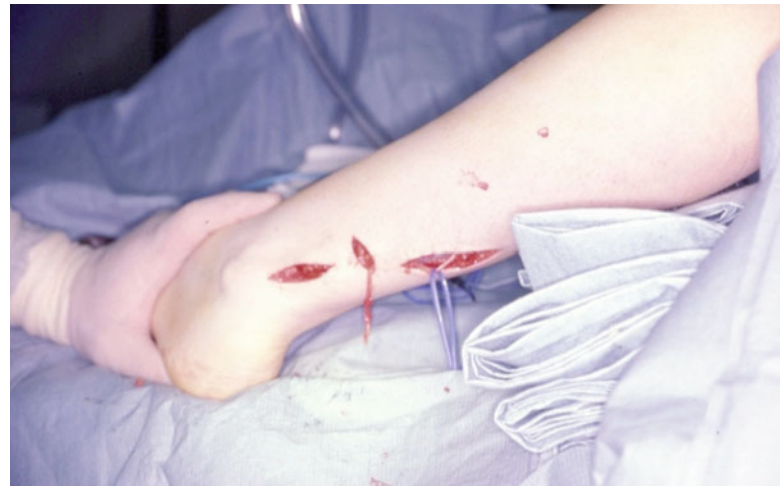

Fig. 16.11 The sural nerve may be harvested through multiple small incisions in the lower leg

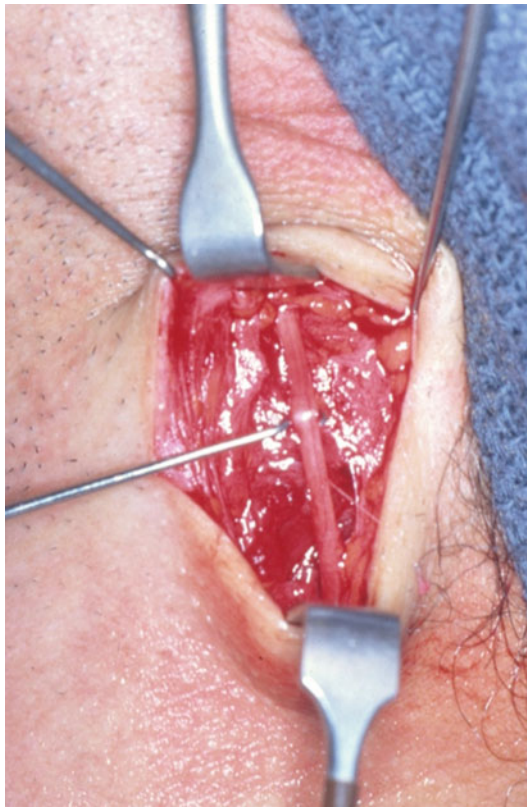

Fig. 16.12 The greater auricular nerve is harvested from the neck through a horizontal incision

Harvesting the greater auricular nerve results in numbness to the ear, lateral neck, and skin overlying the posterior aspect of the mandible (Fig. 16.12). An additional risk at the donor area in addition to the cervical scar is development of a painful neuroma that may require additional treatment. Patients may prefer that their numbness and/or potential complications be in the foot rather than in the head and neck area, therefore favoring the sural nerve as the preferred donor nerve, and, in fact, improved IAN or LN recovery following nerve repair correlates well with less patient-perceived morbidity from the nerve harvest site [33].

16.3 Factors Affecting Nerve Graft Success

The success and ultimate outcome of a nerve repair or grafting procedure are based on a number of factors, and the more favorable the factors, the better and more predictable the outcome.

16.3.1 Time Since the Injury

In general, peripheral nerve injuries requiring surgical intervention will have better results the earlier the nerve is repaired after injury. Therefore, repairs with or without grafting performed immediately after the injury have better results, with progressively worsening results if done 3, 6, 9, or 12 months or longer after the injury. Wietholter and colleagues reported best results for IAN and LN repair if reconstruction was done within 3 weeks of the injury [53]. Early repair circumvents

major problems encountered with elapsed time such as Wallerian degeneration, atrophy, and fibrosis in the distal portion of the nerve (Fig. 16.1). Atrophy creates a significant size match discrepancy between the nerve graft and either or both nerve stumps. The time factor reflects the rate and extent of degeneration and atrophy of the distal fascicles prior to nerve repair. However, if the injury is primarily a traumatic neuroma without atrophy or degenerative neurologic changes in the distal portion of the nerve, the time factor may not be as important; that is, whether the repair is done at 3 weeks or 2 years may not make a difference in functional outcome.

16.3.2 Type and Extent of Injury

The more localized and confined the injury to the nerve, the less trauma to the nerve, and the shorter the required nerve graft (or possibility of repair without grafting), then the better the outcome. Stretch-type injuries or injuries caused by the injection of alcohol, steroid, or other caustic chemical into or adjacent to a nerve (Fig. 16.3) can cause significant irreversible damage to the nerve, which can extend proximally into the ganglion cell bodies, beyond a surgically accessible area, thus rendering peripheral nerve repair ineffective. In addition, significant ganglion cell death from nerve trauma may occur early (within 90 days) following axotomy injuries, and this further supports the hypothesis that early repairs have improved outcomes.

16.3.3 Vascularity in Host Bed

For a nerve graft to be successful, it must be revascularized rapidly. Therefore, having the graft and the areas of neural anastomosis exposed to adjacent healthy soft tissues will help in this regard. The importance of the access of the nerve repair site to the surrounding vasculature must be weighed against the risk of cicatricial contraction of the soft tissues around the nerve repair site. Therefore, placing a membrane or covering over the nerve repair site to protect the repair or placing the graft inside a bony canal or in an area of significant scar tissue may have poorer results because of delayed revascularization of the nerve repair site and nerve graft if utilized.

16.3.4 Orientation of Nerve Graft Placement

It is important to place a nerve graft so that it is oriented in the same functional direction from which it was harvested. That is, the proximal end of the nerve graft should approximate the proximal end of the host nerve, and the distal end of the graft should anastomose with the distal end of the host nerve. Axoplasmic flow should be maintained in the same direction. Therefore, when a nerve graft is harvested, the orientation should be carefully noted. It is also believed that the direction of axoplasmic flow is not important since the nerve graft essentially functions as a conduit, and anterograde and retrograde flow will be reestablished regardless of the orientation of the nerve graft between the proximal and distal nerve stumps.

16.3.5 Length of Nerve Graft Required

In general, the shorter the nerve graft required, the better the result, and the longer the nerve graft, the less predictable the result. This is due in part to the amount of time it takes for regeneration to occur across each anastomosis area (7–14 days) and along the length of the nerve (0.2–3.0 mm/day). The longer the nerve graft, the more time that is required for regeneration to reach the distal anastomosis of the graft, increasing the risk of atrophy and fibrous ingrowth into the distal anastomosis area, resulting in a poorer outcome (Fig. 16.7).

16.3.6 Quality and Type of Repair

Quality of repair is particularly sensitive to the surgeon's skill and experience. Obviously, the highest quality repairs yield the best results. A high-quality repair includes atraumatic management of the proximal and distal ends of the host and graft nerves and meticulous

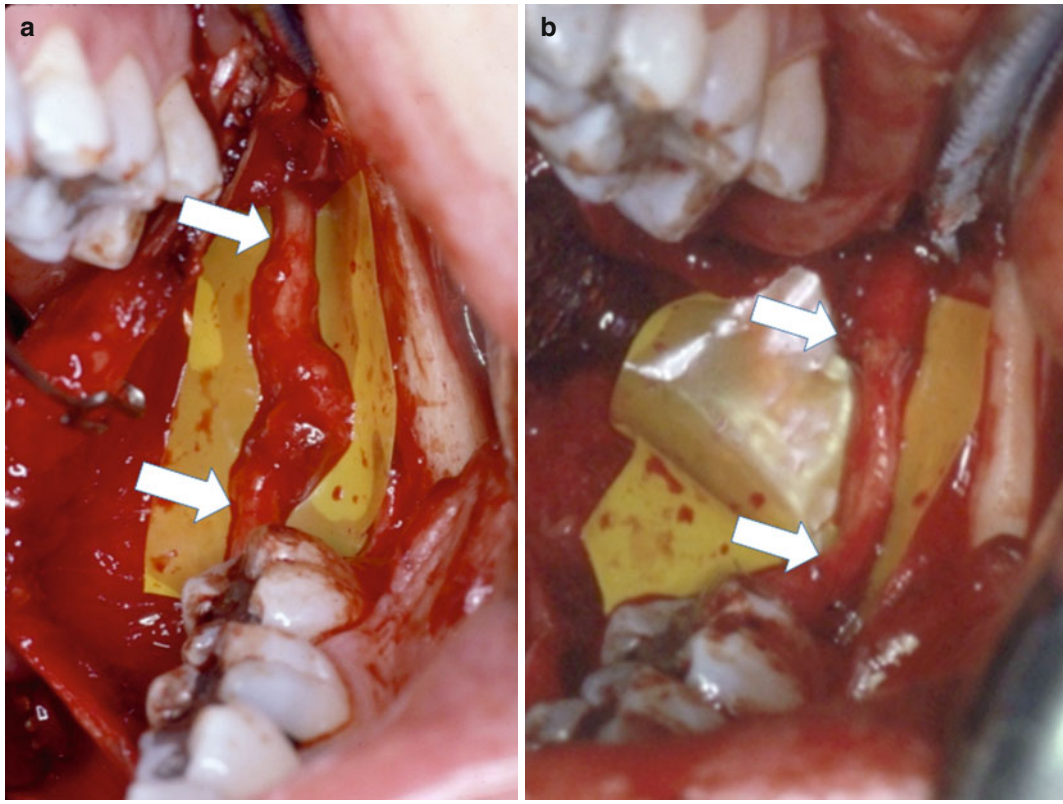

Fig. 16.13 (**a**) Lingual nerve with a large neuroma (between *arrows*) as a result of an impacted third molar removal. (**b**) The nerve has been repaired with a sural nerve graft without any tension on the nerve segments. The distal and proximal anastomoses are delineated by *arrows*

neurorrhaphy techniques. The TN branches are polyfascicular without grouping and have a large number of fascicles, so epineurial repair is the most logical and appropriate technique (Fig. 16.6). Depending on the situation, 8-0 to 10-0 monofilament nylon suture can be used for the repairs. Minimizing the number of sutures (3–6 is optimal) is helpful as long as the approximation of the nerve graft to the nerve stumps is accurate. It is important to attempt to suture only the epineurium and not pass the needle and suture through the fascicles, since this can create more fascicular damage and scarring, yielding a poorer result.

16.3.7 Tension on Repaired Nerve

The nerve should be repaired or grafted with no tension on the nerve segments and areas of anastomosis (Fig. 16.13a, b). Excessive tension can cause breakdown at the area of anastomosis with scar tissue formation, resulting in a poor outcome. The host nerve should be prepared prior to harvesting the graft so that graft length can be determined as accurately as possible. It must be remembered that the sectioned host nerve segments will retract, yielding a larger defect. Additionally, a harvested nerve graft shrinks in length by approximately 20 %, and additional length may be lost in final preparation of host and nerve graft ends. Therefore, the nerve graft harvested should be at least 25 % longer than the initially measured host nerve defect to compensate for these predictable changes.

16.3.8 Preparation of the Host Nerve

A good outcome requires complete removal of the area of injury and assurance of healthy, viable

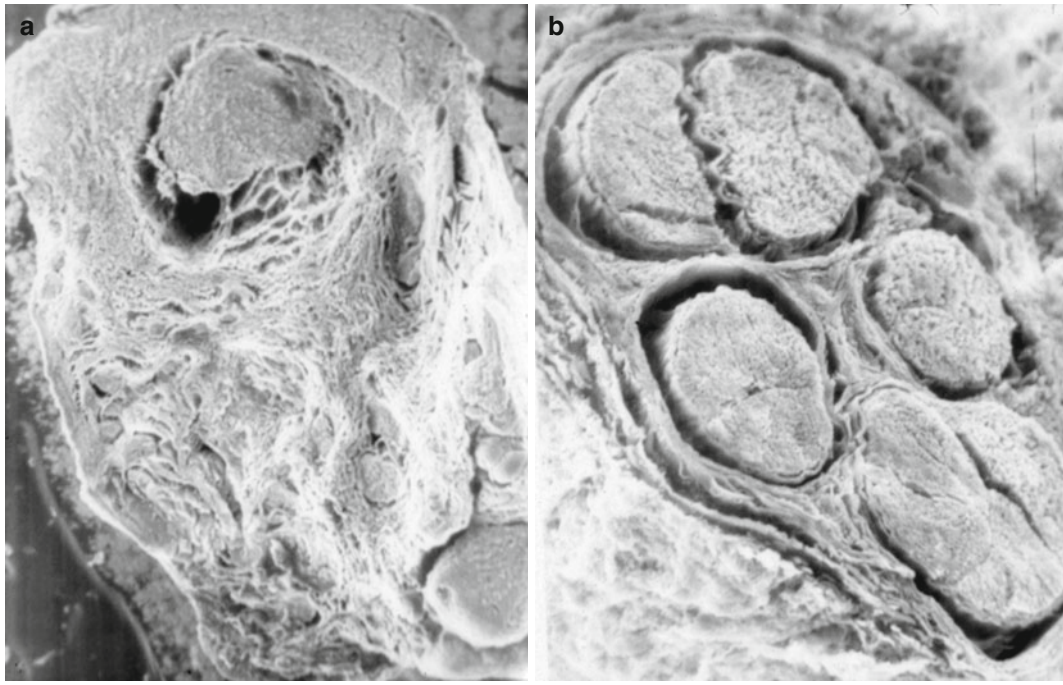

Fig. 16.14 (**a**) Frozen section of an injured proximal nerve segment shows significant fibrosis and no viable fascicles. (**b**) Frozen nerve section further proximal demonstrates viable nerve tissue

nerve tissues at the proximal and distal stumps. Frozen sections for histological assessment of the proximal and distal stumps may be helpful to determine when good, viable nerve tissue has been reached [51]. In the distal end, there may be degenerative changes (Wallerian degeneration) involving the fascicles. However, it is important to be sure that no significant fibrosis or other obstructions remain in the distal portion of the host nerve (Fig. 16.14a, b). The proximal and distal nerve stumps should be prepared with 1.0-mm resections until healthy fascicles are encountered. Of course, with continued incremental resection, the need for nerve grafting, or defect management, increases significantly, but this is a necessary step to ensure that scar tissue does not remain at the host nerve stumps since this would result in a poor outcome.

16.3.9 Age of Patient and Other Health Factors

In general, younger patients have the best results, and elderly patients have the poorest results following nerve repair or grafting. Children have a greater ability to centrally adapt to altered nerve programming, greater regenerative capabilities, and greater healing and metabolic rates than older patients. Systemic factors that can adversely affect outcome include connective tissue and autoimmune diseases (e.g., scleroderma, mixed connective tissue disease, rheumatoid diseases, and systemic lupus erythematosus), diabetes mellitus, vascular and bleeding disorders, inherited or acquired neuropathies, alcoholism, smoking, and others. These factors must be considered when counseling patients about risks, complications, and expected outcomes following nerve repair.

16.4 Expected Outcomes

Many factors influence the quality of results following nerve repair. If the donor nerve and other success factors are all favorable, then good results can be expected. The definition of a successful and acceptable outcome varies widely among patients and surgeons, since there is no accepted standard assessment protocol. The quality of

outcome for a given patient may not be predictable, but the more favorable the factors affecting success, the greater the potential for a good outcome. It must be understood that the best result may not be able to restore function to the preinjury level. With LN injury, return of taste sensation is unpredictable and should not be expected.

Wietholter and colleagues found better results for IAN repair with end-to-end anastomosis than with nerve grafting [53]. This has been the senior author's experience as well. Therefore, with IAN injuries, the possibility of decortication of the mandible over the distal portion of the IAN should be evaluated, and the distal portion of the IAN and mental nerve should be posteriorly repositioned to facilitate end-to-end repair before considering a nerve graft. Hessling et al. reported that only 40 % of patients who underwent IAN reconstruction and 35 % who underwent LN reconstruction have good results. They recommended reconstruction of these nerves only if the patient has pain in addition to loss of sensitivity [21]. Bagheri and colleagues found an 81 % IAN restoration of acceptable levels of neurosensory function. They report that the likelihood of regaining neurosensory function threshold drops significantly at 12 months after nerve injury and at 51 years of age [4]. Zuniga reported on outcomes of nerve repair in ten patients; both patients and surgeon rated the overall outcomes as mostly good, although there were differences in specific outcome ratings by surgeon and patients [57]. Donoff and Colin reported improvement in 63 % of their patients who underwent LN repair (31 nerves): 77 % in the anesthesia group and 42 % in the pain-paresthesia group. Overall, improvement was seen in 77 % of patients who underwent IAN repair [15].

Less favorable results in some studies may be related to unfavorable factors affecting outcome. Assessment of the literature indicates that LN repairs are less successful than other nerve repairs. Perhaps difficulty in surgical access and constant mobility of the area after surgery (i.e., eating, swallowing, and speaking) may contribute to the lower success rate. Also, the LN is the largest branch of the trigeminal system. Most surgeons use only a single-strand graft for repair of any of the TN branches, resulting in a significant mismatch in size and fascicular characteristics, which may contribute to a less satisfactory outcome. Use of cable grafting may improve the results for some patients [54, 55]. Bagheri and colleagues performed a chart review of 222 patients receiving a LN repair with a follow-up of at least 1 year. They found that the microsurgical repair of LN injury has the best chance of successful restoration if done within 9 months of injury, and the likelihood of recovery after nerve repair decreases progressively when the repair occurred more than 9 months after injury and with increasing patient age (5.5 % decrease in the chance of recovery for every year of age in patients 45 years old or older [3]).

16.5 Nerve Grafting with Other Tissues

Alternative tissues such as veins, collagen conduits and filaments, and perineurial tubes have been used in the past for nerve repair. The majority of human and animal studies have involved vein grafts. Pogrel and Maghen [37] and Miloro [31] (rabbit model) (2001) showed that vein grafts may be useful for TN repair. Tang and colleagues reported on a technique in which a vein was taken from the forearm and reversed to bridge digital nerve defects [45]. For nerve defects >2.0 cm, normal nerve slices were inserted inside vein conduits. Follow-up revealed excellent recovery in two digital nerves, good in nine, fair in five, and poor in two.

Chiu and Strauch reported a prospective comparative clinical study evaluating direct nerve repair, nerve grafting, and vein grafting for distal sensory nerve defects <3 cm. A total of 34 nerves were repaired: 15 with a venous nerve conduit, 4 with a sural nerve graft, and 15 with direct repair. Significant symptom relief and satisfactory sensory function return were observed in all patients. Two-point discrimination measurements indicated the superiority of direct repair, followed by conventional nerve grafting, and then vein grafting. However, the universally favorable patient acceptance and the return of measurable two-point discrimination indicated the effectiveness of autogenous

vein grafts as nerve conduits when selectively applied to bridge a small nerve gap (<3 cm) on nonessential peripheral sensory nerves [12].

Walton and colleagues reported a retrospective study on the use of autogenous vein grafts in 22 digital nerve repairs. Two-point discrimination averaged 4.6 mm for 11 acute digital nerve repairs using vein conduits 1–3 cm in length. Delayed digital nerve repair with vein conduits yielded poor results. Comparing end-to-end digital nerve repairs and digital nerve grafting suggests that repair of 1- to 3-cm gaps in digital nerves with segments of autologous vein grafts appears to give results comparable to those of nerve grafting [49]. Some investigators have suggested that the vein graft should be used in an inside-out fashion since the outer surface of the vein contains the neurotrophic and neurotropic factors to help promote and support nerve growth from the proximal nerve stump.

However, a major concern with autogenous vein grafts is that they have little mechanical resistance to kinking and collapse [51]. Tang and colleagues demonstrated that repair of digital nerves with gaps ranging from 4 to 5.8 cm using vein conduits yielded no detectable recovery of sensibility in autonomous areas of these nerves and no sign of recovery of the innervated muscles during follow-up [45]. Re-exploration revealed that the vein conduits used for repair of the median nerves were constricted by surrounding scar tissue; axon regeneration was precluded [46].

16.6 Allograft Nerve Grafts

The cadaveric nerve allograft provides an unlimited graft source acting as viable nerve conduits without the morbidities associated with autogenous nerve harvesting. This grafting method has the advantage of harvesting the same nerve from the host to be grafted to the recipient site providing the best nerve graft characteristics (nerve diameter, fascicular pattern, etc.). Host motor and sensory axons grow to reach the host target via those conduits. Function is provided by the regenerating autologous nerves, and this regeneration is supported by allogeneic cells. To ensure Schwann cell viability and minimal fibrosis, the allograft must be revascularized in an early posttransplant period [40].

These allogeneic nerve grafts are rapidly rejected unless appropriate immunosuppression is achieved. The toxicity associated with immunosuppression required to promote graft acceptance must be compared with relative benefits of reinnervation before nerve allotransplantation can be safely applied in routine practice [40]. Mackinnon and colleagues treated seven patients with allograft nerve transplantation, up to 37 cm in length, to the extremities with immunosuppression therapy started several days before surgery. The average time of immunosuppressive therapy was 18 months with no posttreatment evidence of adverse reactions, and only one nerve graft was rejected. The other patients at longest follow-up had light touch, hot and cold, as well as pain sensations, but no two-point discrimination [27]. Optimal treatment methods for nerve allograft transplantation must minimize or prevent rejection and permit nerve regeneration at the same time.

One option is the use of processed allografts such as AxoGen Avance® (AxoGen Inc., Alachua, FL), a human decellularized allograft product (Fig. 16.15). Processed allografts retain the scaffold of nerve tissue but are made to be non-immunogenic and inert in the body by a variety of processing methods. Examples of processing techniques include the following: repeated freeze-thaw cycles, exposure to radiation, extended storage in cold University of Wisconsin solution, and decellularization with detergents. Processed allografts provide a biological substrate for nerve regeneration without the requirements for immunosuppression [40].

Whitlock and colleagues used a rat model to compare isograft, NeuraGen (type I collagen conduit), and processed rat allografts comparable to AxoGen Avance®. In the long sciatic nerve gap model (28 mm), isograft was superior to processed allograft, which was superior to NeuraGen conduits at 6 weeks postoperatively. The authors conclude that in the long-gap model, nerve grafting alternatives fail to deliver the regenerative

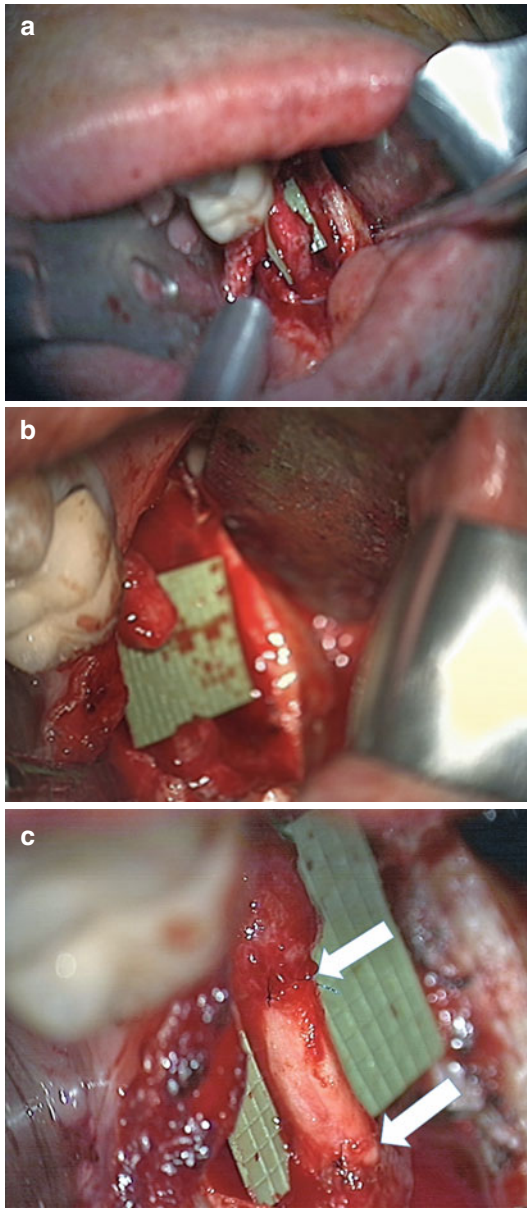

Fig. 16.15 (**a**) Left IAN neuroma. (**b**) The neuroma has been excised. (**c**) The IAN has been repaired with an Avance decellularized cadaveric nerve. A 3–4-mm diameter × 30-mm Avance nerve graft was trimmed to span the 10-mm defect. The *arrows* delineate the graft (Photos courtesy of Martin Steed, DDS, Atlanta, Georgia)

advantages of an isograft. However, in the short sciatic nerve gap model (14 mm), there was no significant difference between the three groups relative to nerve regeneration at 22 weeks [52]. Although the use of processed decellularized cadaveric allografts look promising for nerve injury repair, there is only one study (abstract) available to determine the efficacy of using this graft system for repair of LN or IAN nerve injuries [19]. In 8 patients (5 LN and 3 IAN) who had an Axogen Avance® nerve graft, 4 patients had some recovery, 1 had minimal recovery, and 3 patients had no recovery of sensation. At best this could be seen as a 50 % success with the use of this technique, but more data is needed for adequate interpretation of the usefulness of this graft option.

16.7 Alloplastic Nerve Grafts

End-to-end suture neurorrhaphy of nerves and autologous nerve graft are the "gold standard" for repair and reconstruction of peripheral nerves. However, this treatment may be associated with a variety of clinical complications, such as donor-site morbidity, limited availability, nerve site mismatch, and the formation of neuromas [42]. Nerve conduits provide a channel for direction of axonal sprouts from the proximal stump to the distal nerve stump. In addition to this, they allow diffusion of neurotrophic and neurotropic factors secreted by the Schwann cells of the distal stump and minimize infiltration of fibrous scar tissue. A variety of synthetic materials are available (e.g., silicone, polyglycolic acid, glycolide trimethylene carbonate, and poly lactide-co-caprolactone) [10]. This section will present the alloplastic options to treat nerve defect injuries.

16.7.1 Nonresorbable Materials

Silicone is a permanent conduit material that has been used for nerve grafting. However, long-term entubulization of a nerve produces localized compression with resultant decreased axonal conduction, although the total number of nerve fibers and size of the axons remain constant. However, alterations in the blood-nerve barrier occur, followed by demyelination of the nerve fibers [25, 26]. Silicone tubes used for neural conduits must be removed in order to achieve

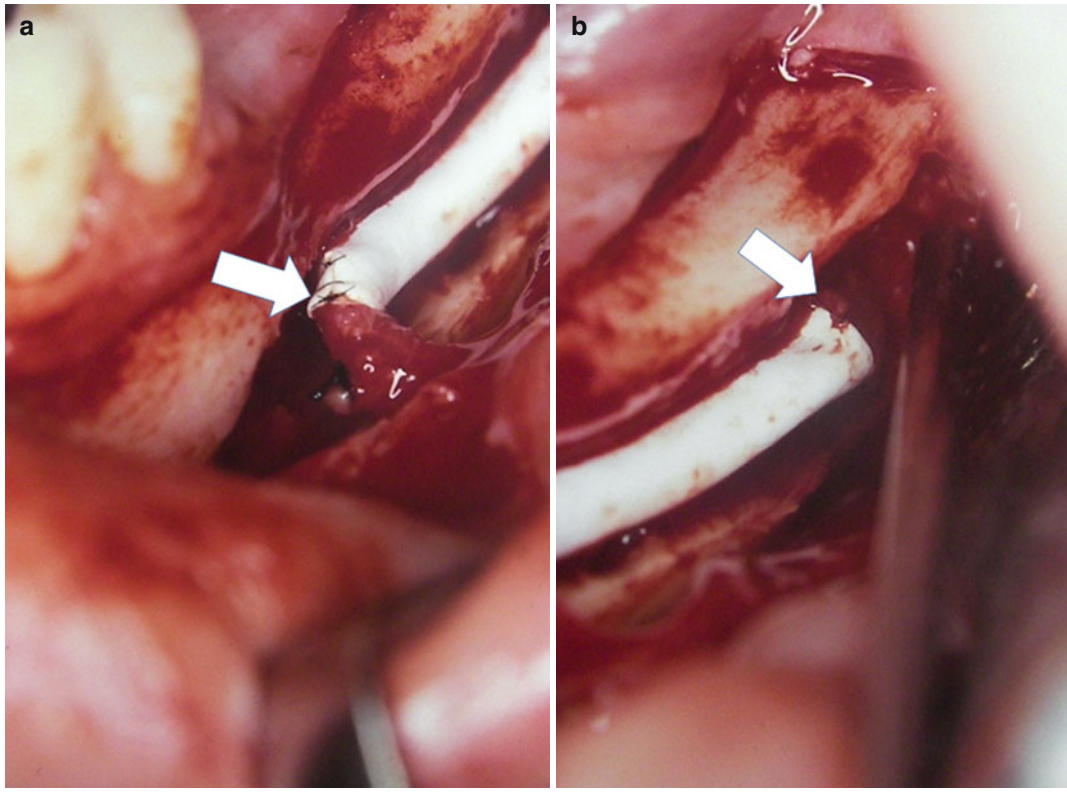

Fig. 16.16 (**a**) Gore-Tex conduit used for nerve reconstruction, demonstrating the distal repair (*arrow*). Due to distal nerve atrophy, the distal end of the graft has been narrowed to conform to the diameter of the distal nerve segment. This modification can be used for other conduit products. (**b**) The proximal repair is seen (*arrow*). However, Gore-Tex grafts are not recommended for repair of trigeminal nerve branches

a positive outcome [14]. Similar unfavorable outcomes occur when using Gore-Tex (expanded polytetrafluorethylene) grafts (WL Gore and Associates, Inc, Flagstaff, AZ) as a nerve graft conduit (Fig. 16.16a, b). Although animal studies have shown promise in the use of Gore-Tex for a nerve continuity defect [32], the clinical studies indicate that Gore-Tex tubing is not effective and therefore not recommended in the repair of continuity defects of IAN and LN. The Gore-Tex tubing collapses following surgery since it has little inherent strength which impedes neural regeneration [36, 38]. Other nondegradable materials with poor results are elastomer hydrogel or porous stainless steel. These artificial materials have the disadvantage of engendering chronic foreign body reactions due to scar formation, inflexibility, and lack of stability [41], and these are not used for TN repair.

16.7.2 Biodegradable Synthetic Materials

The biodegradable or resorbable nerve tubes are an alternative for repairing peripheral nerve defects in order to avoid the problems associated with nondegradable polymeric conduits, such as foreign body reactions.

16.7.2.1 Polyglycolic Acid

Polyglycolic acid (Dexon, American Cyanamid Co, Wayne, NJ) is a bioabsorbable substance that is currently used as a suture material [20] and in mesh form to invest internal organs injured as a result of trauma [28]. It is absorbed in the body via hydrolysis, begins to breakdown at 3 months, and is resorbed within 6–8 months. A bioabsorbable polyglycolic acid conduit has been developed for nerve grafting in which the nerve gap

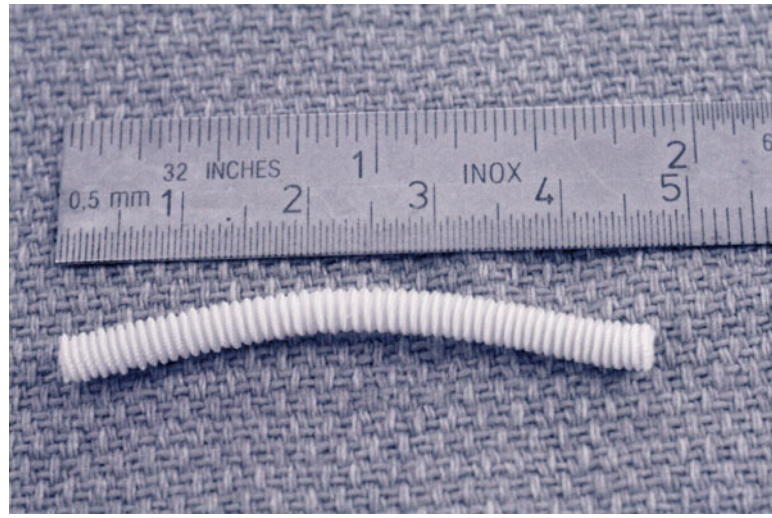

Fig. 16.17 Neurotube is a bioabsorbable polyglycolic acid tube with porosity, flexibility, and corrugation to resist occlusive forces

is ≥8 mm but ≤3 cm (Neurotube, Synovis Life Technologies Inc., St.Paul, MN) (Figs. 16.17 and 16.18a–g). Characteristics of this tube include the following: (1) porosity, which provides an oxygen-rich environment for the regenerating nerve; (2) flexibility, to accommodate movement of joints and associated tendon gliding; (3) corrugation, to resist the occlusive force of surrounding soft tissue; and (4) bioabsorbability, eliminating the need for removal at a subsequent operation. This corrugated tube has available internal diameters from 2.3, 4.0, to 8 mm and lengths from 2 to 4 cm [5, 18].

Weber and colleagues reported a prospective study on 136 nerve repairs in the hand, divided into two groups: group 1 consisted of standard repair with either end-to-end anastomosis or nerve graft and group 2 consisted of nerve repair using a Neurotube conduit (Fig. 16.17). Although there were no statistical differences between the two groups overall, two-point discrimination was better in the Neurotube group (6.8 ± 3.8 mm) than in the direct anastomosis or nerve graft group (12.9 ± 2.4 mm). The Neurotube conduit provided superior results and eliminated donor-site morbidity [50]. Mackinnon and Dellon reported good to excellent results in 86 % of digital nerve repairs in 15 patients using Neurotube [29]. Also, it is recommended to fill the tube with heparinized saline. Casanas et al. studied 17 patients with digital nerve defects ranging from 2 to 3.5 cm grafted with Neurotube with good results [9]. Navissano and colleagues reported on using Neurotube to repair facial nerve defects from 1 to 3 cm with good results in five of seven patients [35].

Few articles have been published on Neurotube as an alloplastic material for TN repair. Crawley and Dellon reported an isolated case in which a 2.0-mm diameter Neurotube conduit was used in a 51-year-old woman to repair a right IAN 16 months following injury. The Neurotube conduit was filled with autologous serum to prevent blood clot formation. At 12 months after surgery, pressure and vibratory perception were similar to those of the contralateral lip and chin area [13].

The authors have utilized the Neurotube conduit for IAN and LN grafting with good preliminary results. The technique includes preparation of the proximal and distal ends of the host nerve and of a conduit graft that is at least 1 cm longer than the size of the defect. Three to four 8-0 to 10-0 nylon sutures are passed through the tube 5 mm from the end, through the epineurium of the proximal nerve stump, and back out through the tube in a horizontal mattress fashion. After all sutures are passed, the sutures are then gently pulled to deliver the proximal end of the nerve within the tube several millimeters (Figs. 16.17 and 16.18). The same horizontal mattress procedure is carried out for the distal end of the nerve. If there is a discrepancy in the sizes of host nerve end and tube diameter, the tube can be slit at the

end to allow expansion or contraction to correlate with the host nerve diameter. The artificial nerve conduit is then filled with a solution containing 1,000 U of heparin per 100 mL of isotonic saline to help prevent blood clot formation, which could impede axonal regeneration.

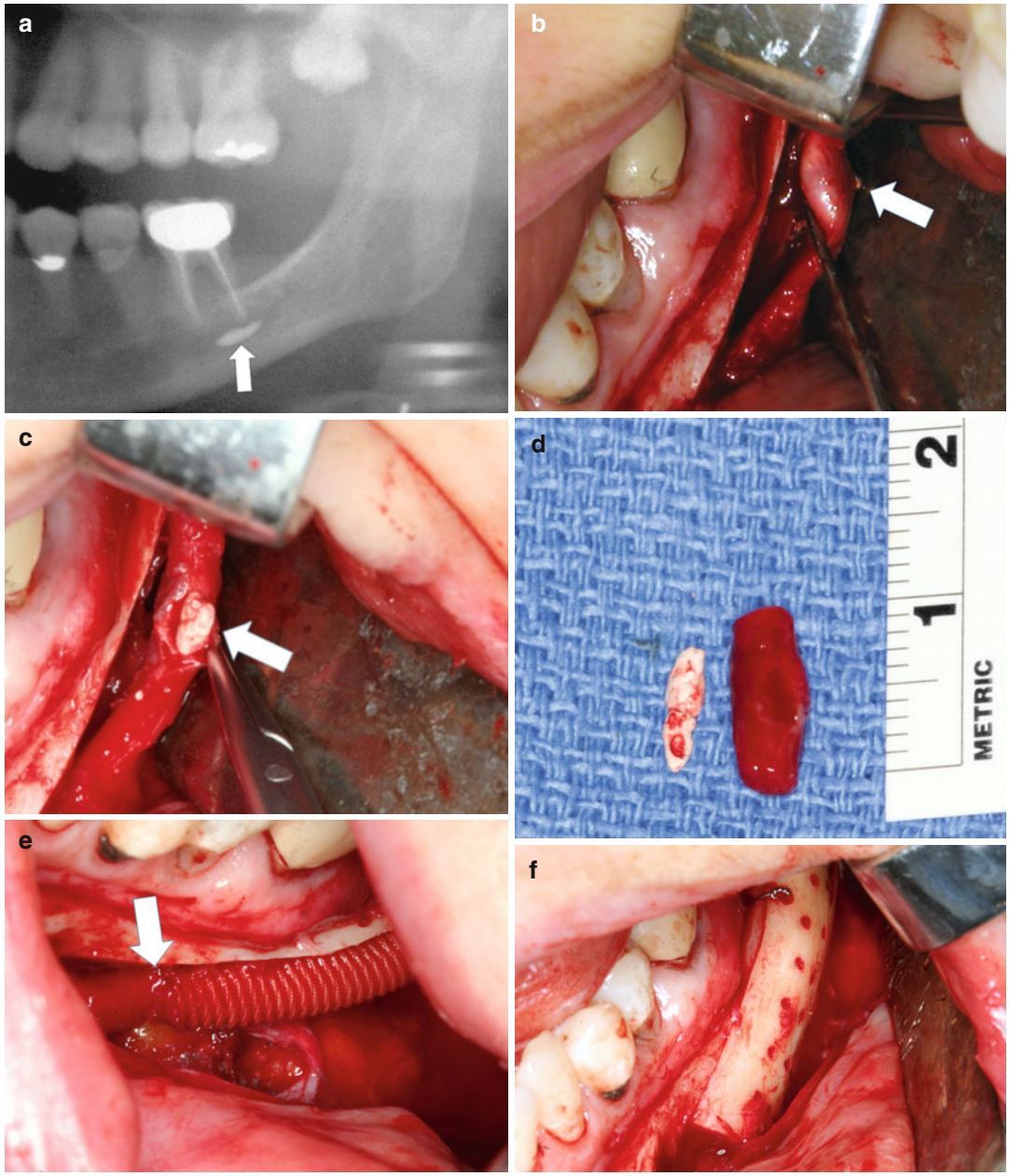

Fig. 16.18 (**a**) Radiograph shows foreign material (*arrow*) in the IAN canal following root canal treatment resulting in a painful dysesthesia to the distribution of the IAN. (**b**) Following decortications of the mandible, the IAN has been lateralized from the mandible. The *arrow* points to the nerve lesion. (**c**) An incision into the nerve shows a foreign body within the nerve (*arrow*). (**d**) The IAN lesion has been resected, and the foreign body removed. (**e**) The nerve has been repaired with a 2.3-mm diameter Neurotube with the distal repair observed (*arrow*). (**f**) The lateral cortical bone that was removed for access to the IAN is replaced in position. The holes placed in the bone are to aid in revascularization of the repair site. (**g**) Radiograph shows the replaced buccal cortical bone

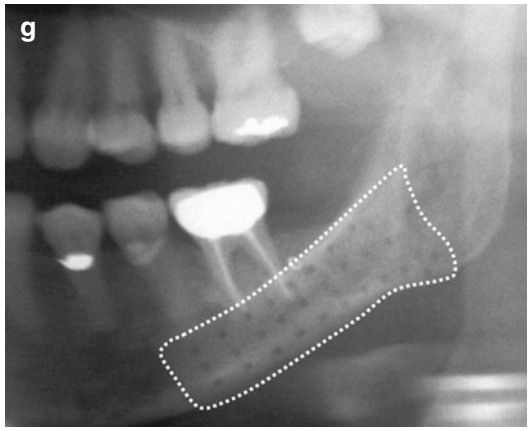

Fig. 16.18 (continued)

16.7.2.2 Polyesters and Copolyesters

Poly(DL-lactide-e-caprolactone) Neurolac nerve guide (Polyganics Inc. Groningen, NL) is another synthetic nerve conduit with a 3.5-cm length and a variable 1.5- to 10-mm internal diameter. The tube is less flexible, tends to swell, and takes 16–24 months to resorb. Bertleff and colleagues reported results in 54 patients with digital nerve injuries with controls using direct repair or nerve grafting and the experimental group treated with Neurolac conduits [7]. Interim results showed comparable outcomes, but at longer follow-up, the Neurolac group did not show better function and had significantly more complications related to the initial stiffness of the conduits but subsequent collapse during the absorption phase [30]. Chiriac and colleagues treated a series of 23 patients in a total of 28 nerve lesions (arm, forearm, wrist, palm, and fingers). Defects averaged 11.03 mm and were repaired using Neurolac. After an average of 21.9 months, they observed eight complications with the most serious being two fistulizations of the Neurolac device close to a joint and one neuroma. They concluded that the results do not support its use in repairing hand nerve defects [11]. Alternatively, Battiston and colleagues reported on 28 digital nerve repairs with Neurolac with 93 % good to excellent results [6]. No studies have been done on the use of Neurolac in TN repair.

16.7.2.3 Collagen

Semipermeable collagen type 1 nerve guides have been developed (Collagen NeuraGen Nerve Guide, Integra NeuroSciences, Plainsboro, NJ). Type 1 collagen-based implants support and guide tissue regeneration in vivo, have low immunogenicity, and are biocompatible (Fig. 16.19a, b). Tube lengths are 2 to 3 cm with internal diameters ranging from 1.5 to 7 mm with an absorption rate of 4–8 months. Ashley and colleagues used NeuraGen nerve conduits in patients with brachial plexus birth injuries with four of five patients showing good recovery at 2 years post-surgery [2]. Lohmeyer and colleagues used NeuraGen grafts in hand surgery reporting four of six patients with excellent results at 1 year post-surgery [23]. Farole and Jamal described the results of using NeuraGen cuffs placed around nerve repair sites in eight patients with nine repairs. Following primary nerve repair, a NeuraGen conduit was split

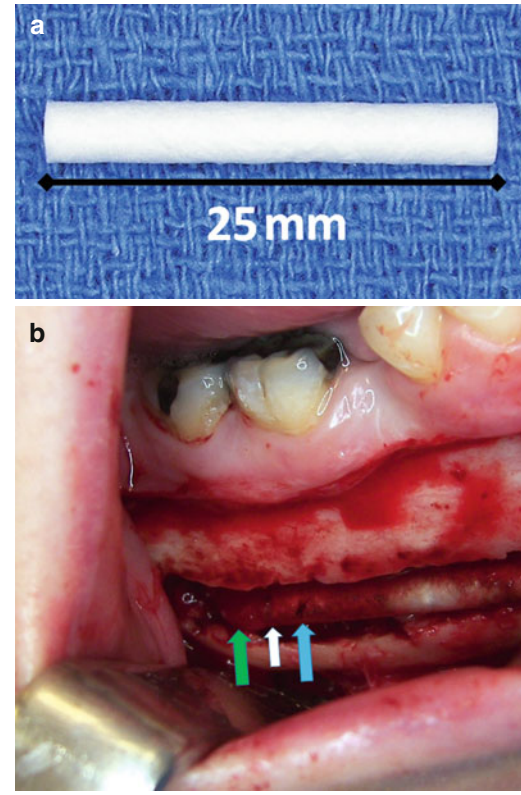

Fig. 16.19 (**a**) A collagen NeuraGen nerve guide can be used for nerve repair. (**b**) The NeuroGen tube has been used to repair the IAN. The *green arrow* shows the proximal nerve end. The *white arrow* shows where the IAN inserts into the NeuroGen tube. The *blue arrow* points at one of the three sutures used to deliver the IAN within the conduit and stabilize it in place

longitudinally and encased around the repair site with at least 1.5 cm of margin. At 1–2.5 years follow-up, four repairs were found to have good improvement, four had some improvement, and one had no improvement [17]. NeuroMatrix and Neuroflex (Collagen Matrix Inc., Franklin Lakes, NJ) also make a nerve cuff that is described as nonfriable, crimped, semipermeable, tubular membrane matrix with type 1 collagen. The length is 2.5 cm and internal diameters from 2 to 6 mm with 4 to 8 months for absorption.

Since these absorbable conduits disintegrate, the problems associated with permanent tubing (i.e., Silastic, Gore-Tex), including compression and demyelination, are eliminated. The superior results achieved with nerve graft conduits are related to the elimination of the problems associated with harvested nerve grafts, host-donor differences in diameter, mismatches in number and pattern of fascicles and cross-sectional shape and area, as well as morbidity of the donor area. However, absorbable conduit grafting results will still be affected by such factors as time since injury, type and extent of injury, vascularity, graft size match, length of nerve graft required (results are good for defects <3 cm), quality of the repair (surgical skill), tension on the repair site, preparation of the host nerve, age of the patient, and other health factors.

Meeks and Coert recommend Neurotube as the preferred resorbable conduit for nerve repair following their extensive review of the various options [30]. Shin et al. performed a rat study creating 10-mm gaps in the sciatic nerve with four groups: Group I had reversed autografts, Group II had Neurolac conduits, Group III had NeuraGen conduits, and Group IV had Neurotube conduits. Groups I and II had the best results with no significant difference between them. Group VI had the poorest results but in part due to the diameter of the sciatic nerve was 1.5 mm, and the smallest Neurotube was 2.3 mm, while the other conduits were the appropriate size [39]. This study further supports the importance of having a coordinated diameter size of the conduit to the host nerve.

16.8 Molecular and Cell Therapy

Experimental studies have shown that the use of conduits seeded with cultured Schwann cells improves nerve regeneration. The use of fetal and adult progenitor neuronal cells and bone marrow stem cells are alternative techniques to the use of Schwann cells. Liu and colleagues investigated the effect of the adipose-derived stem cells (ADSCs) on peripheral nerve repair. They evaluated nerve regeneration across a 15-mm lesion in the sciatic nerve by using an acellular nerve injected with allogenic ADSCs. Results showed that the recovery of the ADSC-treated group was significantly better than that of the control group ($p < 0.05$). They conclude that the ADSC transplantation represents a powerful therapeutic approach for peripheral nerve injury, although the detailed mechanism by which the ADSCs promote peripheral nerve regeneration is being investigated [22]. Zhao and colleagues studied eighteen mice divided into three groups ($n = 6$ for each group) for nerve repair with nerve autograft, acellular nerve graft, and acellular nerve graft supplemented with bone marrow mesenchymal stromal cells (MSCs) and fibrin glue around the graft. The mouse static sciatic index was evaluated by walking-track testing every 2 weeks. The results showed that the nerve repair by the nerve autografting obtained the best functional recovery of the limb. The nerve repair with acellular nerve graft supplemented with MSCs achieved better functional recovery and higher axon number than that with the acellular nerve graft alone at 8 weeks post-surgery [56].

Another approach that has been studied is the incorporation of neurotrophic and neurotropic factors (e.g., basement membrane laminin) into nerve conduits in order to support nerve growth and improve the nerve regeneration process. The use of these techniques has been largely experimental to date. Cell therapy is limited by the technical and logistical difficulties in culturing and expanding these cells in vitro [10].

16.9 Summary

Nerve repairs and nerve grafting techniques have been around for many years. Autogenous nerve grafts have worked reasonably well in the right circumstances but are associated with difficulties in achieving a proper donor-host match as well as adverse postsurgical sequelae at the donor site. Vein grafts appear to work almost as well as autogenous nerve grafts in digital nerve repairs that require a graft <3 cm in length, but not with TN repairs. Currently, nerve graft materials such as polyglycolic acid tubes and processed decellularized allografts have shown reasonable results without the morbidity of autogenous nerve grafts. However, more research studies using these materials for TN repairs are needed to validate the usefulness and applicability of these procedures. Molecular and cell therapy applied to various nerve grafting techniques will certainly be the future for this challenging field of addressing the peripheral nerve gap.

Conflict of Interest This work has no competing conflict of interest and no funding.

References

1. Abby PA, LaBanc JP, Lupkiewicz S et al (1987) Fascicular characterization of the human lingual nerve: implications for injury and repair. J Oral Maxillofac Surg 45:43
2. Ashley WW, Weatherly T, Park TS (2006) Collagen nerve guides for surgical repair of brachial plexus birth injury. J Neurosurg 105:452–456
3. Bagheri SC, Meyer RA, Khan HA et al (2010) Retrospective review of microsurgical repair of 222 lingual nerve injuries. J Oral Maxillofac Surg 68: 715–723
4. Bagheri SC, Meyer RA, Choo SH et al (2012) Microsurgical repair of the inferior alveolar nerve: success rate and factors that adversely affect outcomes. J Oral Maxillofac Surg 70:1978–1990
5. Barrows TH (1986) Degradable implant materials: a review of synthetic absorbable polymers and their applications. Clin Mater 1:233
6. Battiston B, Geuna S, Ferrero M et al (2005) Nerve repair by means of tubulization: literature review and personal clinical experience comparing biological and synthetic conduits for sensory nerve repair. Microsurgery 25:258–267
7. Bertleff MJ, Meek MF, Nicolai J-PA (2005) A prospective clinical evaluation of biodegradeble Neurolac nerve guides for sensory nerve repair in the hand. J Hand Surg [Am] 30:513–518
8. Brammer JP, Epker BN (1988) Anatomic-histologic survey of the sural nerve: implications for inferior alveolar nerve grafting. J Oral Maxillofac Surg 46:111–117
9. Casanas J, Serra J, Orduna M et al (2000) Repair of digital sensory nerves of the hand using polyglycolic acid conduits. J Hand Surg Br 25:44
10. Chimutengwende-Gordon M, Khan W (2012) Recent advances and developments in neural repair and regeneration for hand surgery. Open Orthop J 6:103–107
11. Chiriac S, Facca S, Diaconu M et al (2012) Experience of using the bioresorbable copolyester poly(DL-lactide-e-caprolactone) nerve conduit guide Neurolac for nerve repair in peripheral nerve defects: report on a series of 28 lesions. J Hand Surg Eur 37:342–349
12. Chiu DT, Strauch B (1990) A prospective clinical evaluation of autogenous vein grafts used as a nerve conduit for distal sensory nerve defects of 3 cm or less. Plast Reconstr Surg 86:928–934
13. Crawley WA, Dellon AL (1992) Inferior alveolar nerve reconstruction with a polyglycolic acid bioabsorbable nerve conduit. Plast Reconstr Surg 90: 300–302
14. Dellon AL (1994) Use of a silicone tube for the reconstruction of a nerve injury. J Hand Surg Br 19:271–272
15. Donoff RB, Colin W (1990) Neurologic complications of oral and maxillofacial surgery. Oral Maxillofac Surg Clin North Am 2:453–462
16. Eppley BL, Snyders RV Jr (1991) Microanatomic analysis of the trigeminal nerve and potential nerve graft donor sites. J Oral Maxillofac Surg 49:612–618
17. Farole A, Jamal BT (2008) A bioabsorbable collagen nerve cuff (NeuraGen) for repair of lingual and inferior alveolar nerve injuries: a case series. J Oral Maxillofac Surg 66:2058–2062
18. Ginde RM, Gupta RK (1987) In vitro chemical degradation of polyglycolic acid pellets and fibers. J Appl Polymer Sci 33:2411
19. Green J (2009) Use of decellularized human nerve grafts for IAN and LN. J Oral Maxillofac Surg 67(Suppl 1): 54–55
20. Herrmann JB, Kelly RJ, Higgins GA (1970) Polyglycolic acid sutures. Laboratory and clinical evaluation of a new absorbable suture material. Arch Surg 100:486–490
21. Hessling KH, Reich RH, Hausamen JE et al (1990) Long-term results of microsurgical nerve reconstruction in the area of the head-neck. Fortschr Kiefer Gesichtschir 35:134–138
22. Liu G, Cheng Y, Feng Y et al (2011) Adipose-derived stem cells promote peripheral nerve repair. Arch Med Sci 4:592–596

23. Lohmeyer J, Zimmermann S, Sommer B et al (2007) Bridging peripheral nerve defects by means of nerve conduits. Der Chirurg 78:142–147
24. Mackinnon SE, Dellon AL (1988) Surgery of the peripheral nerve. Thieme Medical Publishers, New York
25. Mackinnon SE, Dellon AL, Hudson AR et al (1984) Chronic nerve compression an experimental model in the rat. Ann Plast Surg 13:112–120
26. Mackinnon SE, Dellon AL, Hudson AR et al (1985) A primate model for chronic nerve compression. J Reconstr Microsurg 1:185–195
27. Mackinnon SE, Doolabh VB, Novak CB et al (2001) Clinical outcome following nerve allograft transplantation. Plast Reconstr Surg 107:1419–1429
28. Marmon LM, Vinocur CD, Standiford SB et al (1985) Evaluation of absorbable polyglycolic acid mesh as a wound support. J Pediatr Surg 20:737–742
29. Mckinnon SE, Dellon AL (1990) Clinical nerve reconstruction with a bioabsorable polyglycolic acid tube. Plast Reconstr Surg 85:419–424
30. Meek MF, Coert JH (2008) US Fook and Drug Administration/Conformit Europe-approved absorbable nerve conduits for clinical repair of peripheral and cranial nerves. Ann Plast Surg 60:110–116
31. Miloro M (2001) Discussion: the use of autogenous vein grafts for inferior alveolar and lingual nerve reconstruction. J Oral Maxillofac Surg 59:988–993
32. Miloro M, Macy J (2000) Expanded polytetrafluoroethylene entubulation of the rabbit inferior alveolar nerve. Oral Surg Oral Med Oral Pathol 89:292–298
33. Miloro M, Stoner JA (2005) Subjective outcomes following sural nerve harvest. J Oral Maxillofac Surg 63:1150–1154
34. Murray-Dunning C, Mc Arthur SL, Sun T et al (2011) Three-dimensional alignment of Schwann cells using hydrolysable microfiber scaffolds: strategies for peripheral nerve repair. Methods Mol Biol 695:155–166
35. Navissano M, Malan F, Carnino R et al (2005) Neurotube for facial nerve repair. Microsurgery 25: 268–271
36. Pitta MC, Wolford LM, Mehra P et al (2001) Use of Gore-Tex tubing as a conduit for inferior alveolar and lingual nerve repair: experience with 6 cases. J Oral Maxillofac Surg 59:493–496
37. Pogrel MA, Maghen A (2001) The use of autogenous vein grafts for inferior alveolar and lingual nerve reconstruction. J Oral Maxillofac Surg 59:985–988
38. Pogrel MA, McDonald AR, Kaban LB (1998) Gore-Tex tubing as a conduit for repair of lingual and inferior alveolar nerve continuity defects: a preliminary report. J Oral Maxillofac Surg 56:319–321
39. Shin RH, Friedrich PF, Crum BA et al (2009) Treatment of a segmental nerve defect in the rat with use of bioabsorbable synthetic nerve conduits: a comparison of commercially available conduits. J Bone Joint Surg Am 91:2194–2204
40. Siemionow M, Sonmez E (2007) Nerve allograft transplantation: a review. J Reconstr Microsurg 8:511–520
41. Siemionow M, Bozkurt M, Zor F (2010) Regeneration and repair of peripheral nerves with different biomaterials: review. Microsurgery 30:574–588
42. Steed MB, Mukhatyar V, Valmikinathan C et al (2011) Advances in bioengineered conduits for peripheral nerve regeneration. Atlas Oral Maxillofac Surg Clin North Am 19:119–130
43. Svane TJ, Wolford LM, Milam SB et al (1986) Fascicular characteristics of the human inferior alveolar nerve. J Oral Maxillofac Surg 44:431–434
44. Svane TJ (1989) The fascicular characteristics of human inferior alveolar and greater auricular nerves (master's thesis) Waco, TX: Baylor University
45. Tang JB, Gu YQ, Song YS (1993) Repair of digital nerve defect with autogenous vein graft during flexor tendon surgery in zone 2. J Hand Surg Br 18:449–453
46. Tang JB, Shi D, Zhou H (1995) Vein conduits for repair of nerves with a prolonged gap or in unfavorable conditions: an analysis of three failed cases. Microsurgery 16:133–137
47. Terzis JK (1987) Microreconstruction of nerve injuries. WB Saunders, Philadelphia, pp 227–228
48. Trulsson M, Essick GK (1997) Low-threshold mechanoreceptive afferents in the human lingual nerve. J Neurophysiol 77:737–748
49. Walton RL, Brown RE, Matory WE Jr et al (1989) Autogenous vein graft repair of digital nerve defects in the finger: a retrospective clinical study. Plast Reconstr Surg 84:944–949
50. Weber RA, Breidenbach WC, Brown RE et al (2000) A randomized prospective study of polyglycolic acid conduits for digital nerve reconstruction in humans. Plast Reconstr Surg 106:1036–1045
51. Wessberg GA, Wolford LM, Epker BN (1982) Experiences with microsurgical reconstruction of the inferior alveolar nerve. J Oral Maxillofac Surg 40: 651–655
52. Whitlock EL, Tuffaha SH, Luciano JP et al (2009) Processed allografts and type 1 collagen conduits for repair of peripheral nerve gaps. Muscle Nerve 39: 787–799
53. Wietholter H, Riediger D, Ehrenfeld M et al (1990) Results of micro-surgery of sensory peripheral branches of the mandibular nerve. Fortschr Kiefer Gesichtschir 35:128–134
54. Wolford LM (1992) Autogenous nerve graft repair of the trigeminal nerve. Oral Maxillofac Surg Clin North Am 4:447–457
55. Wolford LM, Rodrigues DB (2011) Autogenous graft/allografts/conduits for bridging peripheral trigeminal nerve gaps. Atlas Oral Maxillofac Surg Clin North Am 19:91–107
56. Zhao Z, Wang YU, Peng J et al (2011) Repair of nerve defect with acellular nerve graft supplemented by bone marrow stromal cells in mice. Microsurgery 31: 388–394
57. Zuniga JR (1991) Perceived expectation, outcome, and satisfaction of microsurgical nerve repair. J Oral Maxillofac Surg 49(Suppl 1):77