SURGICAL PRINCIPLES OF PERIPHERAL NERVE REPAIR
Introduction

- Peripheral nerves are the neural structures that connect CNS to the end organs

- PNS consists of:
  - 12 pairs of cranial nerves
  - 31 pairs of spinal nerves

- Unique power of regeneration
Etiology of nerve injury

- Three major causes:
  - Medium to high energy nerve injuries
  - Low energy compressive or ischemic lesions
  - Complex injuries
1. Medium to high energy—Mechanical
   - Transection
     - Partial
       - With lesion-in-continuity
       - Without lesion-in-continuity
     - Complete
       - Sharp transection
       - Blunt transection
   - Contusion/stretch/traction
     - With lesion-in-continuity
     - Without lesion-in-continuity
   - Avulsion
     - Pre-ganglionic
     - Post-ganglionic

2. Low energy compressive/ischemic lesion
   - Compressive neuropathies
   - Compartment syndromes

3. Complex
   - Chemical/injection
     - Direct intraneurial
     - Indirect perineurial
     - Combined
   - Radiation-induced nerve injuries
   - Thermal
   - Electrical
   - Combined
   - Combined
## Classification

### TABLE 230-1  -- Nerve Injury Grading (Sunderland Grading Scale)

<table>
<thead>
<tr>
<th>INJURY GRADE</th>
<th>MYELIN</th>
<th>AXON</th>
<th>ENDONEURIUM</th>
<th>PERINEURIUM</th>
<th>EPINEURIUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (neurapraxia)*</td>
<td>+/-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II (axonotmesis)*</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>+</td>
<td>+</td>
<td>+</td>
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</tr>
<tr>
<td>IV</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>V (neurotmesis)*</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

+, Anatomic structures affected by injury.

* Seddon grading system.
<table>
<thead>
<tr>
<th>Classification of Nerve Injury</th>
<th>Seddon</th>
<th>Sunderland</th>
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<tbody>
<tr>
<td>Neurapraxia</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>Axonotmesis</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>Neurotmesis</td>
<td>IV</td>
<td>V</td>
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Wallerian degeneration = Axonal discontinuity

Conduction block
Axonal discontinuity
Axonal + endoneurial disruption
Perineurial rupture fascicle disruption
Nerve trunk discontinuity
Approach to the patient

- History: pain, sensory loss, weakness
- Clinical examination: general, inspection, joint mobility, motor & sensory testing, autonomic testing & special tests
- Electrophysiology: NCV, EMG
- Imaging
Time of intervention

- Changes following nerve injury:
  - Central cell death, ischemia & fibrosis
  - Target organ changes: muscle atrophy & disappearance of motor end plates- irreversible with time
  - Proximal injury- worse outcome
Time of intervention: early

- Early nerve repair prevents neuronal loss & improves outcome

- With exception of spinal accessory improved results of early repair are found in median, ulnar, radial, musculocutaneous, sciatic, CPN & closed traction BPI

- Limiting factor for early repair: difficult to determine the extent of stump resection
Primary repair: urgent surgery

- Operations done within 3-5 days of injury
- Indication: sharp transection
- Contraindication: poor clinical condition
- Adv:
  - Scar free field
  - Minimal intraneural scarring-less distortion of intraneural architecture- proper fascicular matching
- Disadvantage: EPS may not be available or feasible
Delayed primary repair

- Done after 2-3 weeks
- Good outcome
- Advantages of primary surgery disappears
Secondary repair

- Performed between 3 weeks to 3 months
- Indications: neuroma in continuity
- Adv: 40% of BPI recovers spontaneously- prevents unnecessary surgery
- Disadvantage: exploration in scarred tissue & intraneural scarring & distortion
Indications for surgery

- Paralysis after trauma over the course of a major nerve - including iatrogenic injuries
- Paralysis following closed traction BPI
- Associated vascular or orthopedic injury requiring treatment
- Worsening or failure to improve within expected time period
- Persistent pain
Contraindications

- Poor general condition of the patient
- Uncertainty about viability of the nerve trunks
- Local & systemic sepsis
- Early signs of recovery
Types of surgery

- Primary procedures
- Alternative methods
- Secondary procedures
Alternative procedures

- Direct muscular neurotization
- Nerve conduits
- Interposed freeze-thawed muscle
- Nerve allograft repair
- Central repair
Secondary procedures

- Tendon transfer
- Functioning free muscle transfer
- Arthrodesis
- Tenodesis
- Corrective osteotomy
- Amputation
Principles of nerve repair

- Environment: generous operative field, good illumination, microscope or loupe
- Anesthesia: Short acting paralyzing agent
- Flexibility regarding the position of surgeon & limb
Principles of nerve repair

- Wide exposure
- Sharp dissection in anatomic planes starting from virgin tissues & progressing towards the lesion
- Meticulous hemostasis- bipolar cautery
- Preserving fat & synovium planes- nerve’s gliding planes-

Principles of nerve repair

- Preparing nerve stumps:
  - Circumferential exposure
  - Generous proximal & distal mobilization
  - External neurolysis
  - Use of intra-operative electro-physiology
  - Placement of lateral stay sutures (6-0) - to maintain topographic alignment
Debridement of nerve stumps proximally & distally to remove scar tissue-

scar > scar with some fascicles > pure healthy fascicles (fascicles appear to pout, glossy surface & fine bleeding from vessels)
Principles of nerve repair

- Proper alignment & positioning of nerve stumps & grafts:
  - Longitudinal vessel alignment in epineurium
  - Fascicular alignment
Principles of nerve repair

- Proper suturing:
  - Material: 8-0, 9-0 or 10-0 monofilament nylon
  - Two lateral sutures $180^0$ apart
  - Three to four more sutures may also be placed
  - Tensionless
  - Avoid overzealous suturing - every suture induces fibrosis
Principles of nerve repair

- Use of fibrin glue:
  - Secures the position of anastomosis
  - When used alone: does not provide tensile strength or permit to fish-mouth
  - Clump formation to be avoided
Decompression

- Release of a nerve from external compression

- Types:
  - Open
  - Endoscopic
Neurolysis

- Release of nerve or its part from organized scar
- Types:
  - External
  - Internal
- External neurolysis:
  - Nerve is set free from scar, organized hematoma or bony fragments
  - Released in circumferential manner
  - Epineurium is minimally breached
Neurolysis

- Internal neurolysis:
  - Opening or resection the external epineurium to lyse internal scar
  - Plain of dissection: internal epineurium
  - Not to damage perineurium
  - Used for preparation of nerve ends for grafting, dissection of neuroma in continuity & benign nerve sheath tumor
Direct repair

- Possible in most clean lacerating injuries & when co-aptation can be done without undue tension

- Types:
  1. Epineural repair
  2. Grouped fascicular repair
  3. Fascicular or perineural repair

- Combination of epineural & grouped fascicular repair- most commonly used
Epineural repair

- Traditional method
- Appropriate for monofascicular & diffusely grouped polyfascicular nerve
- Goal: tensionless coaptation of proximal & distal fascicular anatomy
Epineural repair

- Small bite taken from internal & external epineurium
- Perineurium avoided
- Tied with mild to moderate tension
- Disadvantage: precise matching of proximal & distal fascicles may not be possible
Grouped fascicular repair

- Indication:
  - Group of fascicles with specific functions - sensory or motor
  - Nerve requiring split repair
- Debridement & alignment
- Inter-fascicular dissection - within internal epineurium
- Suturing through internal epineurium and perineurium
Fascicular repair

- Indication:
  - Lacerated nerve with identifiable individual motor & sensory fascicles
  - Partial injury to 1-2 fascicles
- Repair under high magnification with 10-0 nylon
- Sutures placed through perineurium
- Avoid endoneurium
- Maximum 2 sutures for each fascicle
- Strengthening by addition of epineural sutures
Epineural vs perineural sutures

Nerve auto graft repair

- Indication: direct repair not possible without undue tension

- Principles:
  - Harvest as much of graft as possible
  - Extremity to be in full extension
  - Proper alignment: proximal nerves- spatial matching & distal nerves- anatomic matching
  - Cable grafting
  - Epineural dissection to create group of fascicles
Nerve auto graft repair

- Graft sutured in epineural & interfascicular epineural technique
- Fish mouth configuration
- 1-2 sutures reinforced with fibrin glue
<table>
<thead>
<tr>
<th>Nerve</th>
<th>Location</th>
<th>Deficit</th>
<th>Contraindication</th>
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<tr>
<td>LACN</td>
<td>Terminal sensory branch of MCN. Located just lateral to biceps tendon in subcutaneous tissue.</td>
<td>Loss of sensation over lateral aspect of forearm</td>
<td>Median nerve injury- significant loss of sensation over dorsolateral thumb</td>
</tr>
<tr>
<td>MACN</td>
<td>Derived from medial cord. Closely follows brachial vein.</td>
<td>Loss of sensation over medial forearm</td>
<td>Ulnar nerve injury</td>
</tr>
<tr>
<td>SSRN</td>
<td>Terminal sensory part of radial nerve. Lies deep to brachioradialis muscle in proximal forearm. Good graft for proximal radial nerve recon.</td>
<td>Anatomical snuff box</td>
<td>Nil</td>
</tr>
<tr>
<td>Sural</td>
<td>Most commonly used donor. Lies deep to deep fascia at proximal leg. Emerge to subcutaneous tissue at midcalf level. Significant contribution from lateral sural branch of peroneal nerve.</td>
<td>Lateral order of the foot</td>
<td>Nil</td>
</tr>
</tbody>
</table>
Harvesting the graft

- Methods:
  - Open
  - Endoscopic

- Incision:
  - Longitudinal
  - Step wise

- Proximal division: deep to deep fascia

- Cut to produce appropriate length
Nerve transfer

- Involves re-assigning an expendable or redundant nerve or its part or branch to a more important nonfunctioning nerve

- Indications:
  - Nerve avulsion
  - Rapid & reliable recovery of motor function in post-ganglionic injury
  - To power free-functioning muscle transfer
Nerve transfer

- Contraindications:
  - Absence of donor nerve
  - Fibrosed, atrophic recipients
  - Repairable rupture or neuroma
  - Poor quality donor

- Principles:
  - Accurate preop documentation & fall-back planning
  - Selection of ideal donor nerve
Nerve transfer

- Transection of recipient as proximal as possible
- Dissection of donor distal to the recipient - to gain length
- Selective neurotization based on fascicular anatomy
- Maintaining orientation
- Tension free repair
Alternative methods

- Direct muscular neurotization:
  - Used when distal nerve stump not available
  - Spreading out fascicle in a fan like manner and burying them in intermysial folds

- Becker M, Lassner F, Fansa H, et al:
Interposed freeze-thawed muscle

- Basal lamina of muscle acts as scaffold for axonal growth
- Problem: axonal growth not target oriented but diffusely over the muscle-
- Promising results for sensory nerve repair-
Nerve conduits

- Tissue engineered bio-artificial tube placed between nerve stumps
- Appropriate directional & trophic cues from migrating Schwann cells & soluble growth factors
- Inner diameter of tube- 20% larger than that of stumps
Nerve conduits

- Placement of single microsuture in U fashion
- Reinforced with glue
- Tube is filled with saline
- Good results for defects <3cm in small nerves

Nerve allograft & vascularized nerve grafts

- Risk of immunosuppression prevents wide spread use of allografts-

- Vascularized nerve graft is useful only in contralateral C7 transfer with interposition ulnar vascularized nerve graft-
Central repair

- Central repair: reimplantation of avulsed spinal nerve-

- Functional benefits have been observed in some cases-

- Should be done within 6 weeks of injury- anterior horn cells become dead after 6 weeks of avulsion-
Secondary procedures

- Indications:
  - To provide additional function
  - Delay between injury & presentation
  - Improvement following previous procedure is less than satisfactory

- Unlike primary procedures these are time-independent
Tendon transfers

- Principles:
  - Maintenance of tissue equilibrium—correction of contractures, joint stiffness etc
  - Availability: removal of donor should not compromise existing function
  - Muscle strength: >85% of normal power or 4/5 power
  - Excursion: amplitude of motion should match & direction of action should match
  - Synergy: transfer of synergistic muscle facilitate rehab
  - Tension: transferred tendon should be at its resting length
Tendon transfer

- **Shoulder function:**
  - Trapezius transfer to prox humerus - abduction
  - Combined LD & teres major transfer - external rotation

- **Elbow function:**
  - Modified Steindler’s flexorplasty: flexor- pronator mass from medial humerus epicondyle transferred 4cm above elbow to anterior cortex of humerus
  - Pec major flexorplasty: insertion sutured to coracoid process & origin to biceps tendon
  - Lat dorsi transfer: flexorplasty with soft tissue coverage

- **Wrist & hand function:** PT to ECRB transfer, opponensplasty
Functioning free muscle transfer

- Involves micro-neurovascular repair of a transplanted muscle
- To restore elbow flexion, shoulder abduction, elbow extension, finger flexion & extension
- Muscles used: gracilis, rectus femoris, LD, pec major, TFL, adductor longus
Special situations
Brachial plexus injury

Open

Closed
Open BPI
Laceration or transection

Sharp injury
Repair within 72 hours

Blunt injury
Tack to adjacent planes- 2ndary repair at 2-3 weeks
Closed injury

- Neuroma in continuity - clinical/ EPS/ radiographic evaluation
  - No regeneration
    - Focal
      - F/U for 2-3 months
  - Regeneration
    - Lengthy
      - F/U for 4-5 months
Non regenerative lesion

Exploration + intraop NAP

NAP +
- Post ganglionic: Neurolysis
- Pre ganglionic: Nerve transfer

NAP-
- Postganglionic: Direct repair or grafting
- Preganglionic: Nerve transfer
Lower limb nerve injury

- Lumbosacral plexus injury can occur following external trauma, orthopedic or obstetric procedures

- Exposure:
  - Obturator & femoral nerve: retroperitoneum & thigh
  - Sciatic nerve: upper sciatic exposure for hip level injury & lower sciatic exposure for thigh level injury
  - Peroneal nerve: exposure is made starting parallel & medial to biceps tendon & extended inferiorly into popliteal fossa & then more laterally over fibular neck
  - Posterior tibial nerve: superior or thigh level exposure & inferior or leg level exposure
Lower limb nerve injury

- Principles of repair are same
- Decision making for surgery within 3-4 months of injury is important
- Results of lower extremity nerve repairs are gratifying
Peripheral nerve tumors

- Benign tumors:
  - Schwannoma:
    - Exposure proximal & distal to tumor
    - Tumor capsule ‘baskets’ nerve fascicles apart- fascicles are adhered & not incorporated into it
    - Intracapsular dissection of tumor with or without internal decompression
    - 1-2 nonfunctioning fascicles enter into the mass- if no NAP- resected with tumor
Peripheral nerve tumors

- Neurofibroma:
  - Until recently NFs were considered not resectable without deficit
  - Fascicles are displaced by tumor
  - Fascicles at poles are identified
  - Sub capsular dissection done
  - 2 or more fascicles are incorporated within tumor mass- if no NAP- resected
  - NAP +: fascicles are traced into & out of the tumor & spared
- Malignant tumors: complete removal with tumor free margins
Future directions

- Major short-coming of nerve repair is axonal loss
  - Nanoscale engineered devices to splice & repair individual axons at cellular level
    Chang WC, Hawkes EA, Kliot M, Sretavan DW: 

- Axonal growth is not synchronous but staggered
  - Short duration electrical stimulation synchronizes axonal growth & enhances motor re-innervation
    Gordon T, Brushart TM, Amirjani N, Chan KM: 
    The potential of electrical stimulation to promote functional recovery after peripheral nerve injury—comparisons between rats and humans. *Acta Neurochir Suppl* 2007; 100:3-11
Future directions

- Use of bio-engineered grafts to allow regenerating axons to respond to appropriate endogenous cues

- Role of stem cells: under investigation
AIIMS data

- Since 1995 to 2002, 505 patients were studied for functional and occupational outcome after surgery for BPI
- In India BPI is most common due to RTA with Rt side involved in 2/3
- 40% cases have pan BPI
- 85% of cable graft yielded improvement in motor power compared 68% in neurotized nerve and 66% in patients undergoing neurolysis
AIIMS data

- Most effective donor nerve for musculocutaneous neurotization was medial pectoral nerve- 63.6% patient improved
- Accessory nerve was most effective for neurotization of suprascapular nerve (100%)
- Thoracodorsal axillary neurotization gave 66.7% improvement
- 50% patients either remained unemployed or had to change their jobs