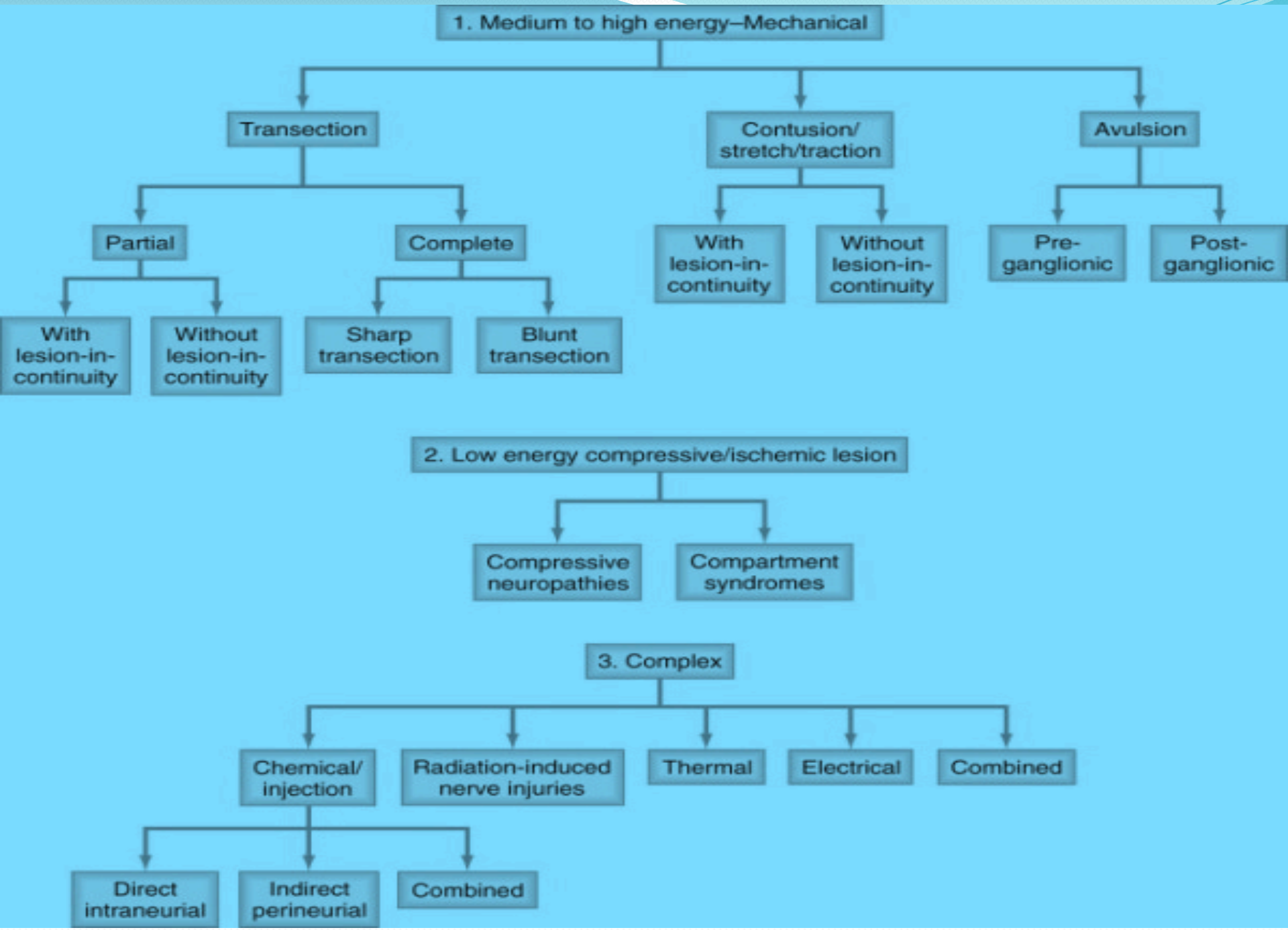
SURGICAL PRINCIPLES OF PERIPHERAL NERVE REPAIR

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

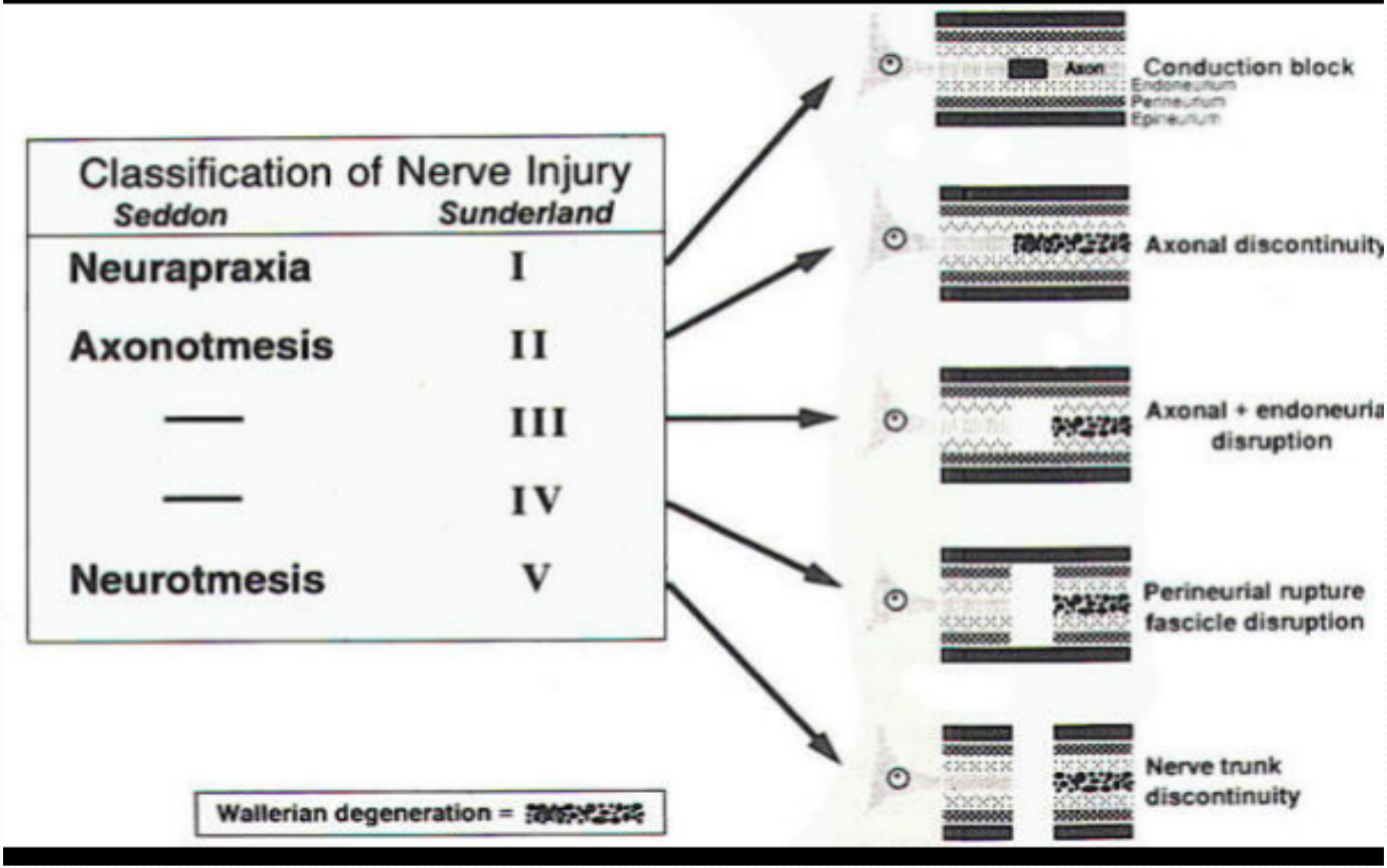
Classification

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

INJURY GRADE	MYELIN	AXON	ENDONEURIUM	PERINEURIUM	EPINEURIUM
I (neurapraxia)*	+/−				
II (axonotmesis)*	+	+			
III	+	+	+		
IV	+	+	+	+	
V (neurotmesis)*	+	+	+	+	+

+, Anatomic structures affected by injury.

* Seddon grading system.



http://www.neurosurgery.tv/wallerian.html

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
  - Ma J, Novikov LN, Kellerth JO, Wiberg M: Early nerve repair after injury to the postganglionic plexus: an experimental study of sensory and motor neuronal survival in adult rats. *Scand J Plast Reconstr Surg Hand Surg* 2003; 37:1-9.
- With exception of spinal accessory improved results of early repair are found in median, ulnar, radial, musculocutaneous, sciatic, CPN & closed traction BPI
  - Merle M, Amend P, Cour C, et al: Microsurgical repair of peripheral nerve lesions: a study of 150 injuries of the median and ulnar nerves. *Peripher Nerve Repair Regen* 1986; 2:17-26.
  - Birch R, Raji AR: Repair of median and ulnar nerves. Primary suture is best. *J Bone Joint Surg Br* 1991; 73:154-157.
  - Kato N, Htut M, Taggart M, et al: The effects of operative delay on the relief of neuropathic pain after injury to the brachial plexus: a review of 148 cases. *J Bone Joint Surg Br* 2006; 88:756-759.
- 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-
  - *The gliding apparatus of peripheral nerve and its clinical significance. Millesi H, Zoch G, Rath T. Ann Chir Main Memb Super 1990;9(2):87-97.*

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

- Perineural suture is better & epineural suture is the main source of infiltration- Millesi H: Interfascicular nerve grafting. *Orthop Clin North Am* 1981; 12:287-301.
- Epineural suture is easier & faster- Orgell M: *Epineurial versus perineurial repair of peripheral nerves.* In: Tertzis J, ed. *Microreconstruction of Nerve Injuries*, London: Saunders; 1987:97-100.
- Restriction of perineural sutures to oligofascicular nerves: Kline D, Hudson A, Spinner R, et al: *Kline & Hudson's Nerve Injuries: Operative Results for Major Nerve Injuries, Entrapments and tumours.* 2nd ed. Philadelphia, Saunders, 2008.
- No discernable difference- Urbaniak J R. Fascicular nerve suture. Clin Orthop Relat Res. 1982 Mar;(163):57-64.

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

Nerve	Location	Deficit	Contraindication
LACN	Terminal sensory branch of MCN. Located just lateral to biceps tendon in subcutaneous tissue.	Loss of sensation over lateral aspect of forearm	Median nerve injury- significant loss of sensation over dorsolateral thumb
MACN	Derived from medial cord. Closely follows brachial vein.	Loss of sensation over medial forearm	Ulnar nerve injury
SSRN	Terminal sensory part of radial nerve. Lies deep to brachioradialis muscle in proximal forearm. Good graft for proximal radial nerve recon.	Anatomical snuff box	Nil
Sural	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.	Lateral order of the foot	Nil

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:
    Refinements in nerve to muscle neurotization. *Muscle Nerve* 2002; 26:362-366.

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-

  Schlosshauer B, Dreesmann L, Schaller HE, Sinis N: Synthetic nerve guide implants in humans: a comprehensive survey. *Neurosurgery* 2006; 59:740-747.
- Promising results for sensory nerve repair-

  Pereira JH, Palande DD, Narayanakumar TS, et al: Nerve repair by denatured muscle autografts promotes sustained sensory recovery in leprosy. *J Bone Joint Surg Br* 2008; 90:220-224.

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-

Weber RA, Breidenbach WC, Brown RE, et al:
A randomized prospective study of polyglycolic acid conduits for digital nerve reconstruction in humans. *Plast Reconstr Surg* 2000; 106:1036-1045

Nerve allograft & vascularized nerve grafts

- Risk of immunosuppression prevents wide spread use of allografts-

  Larsen M, Habermann TM, Bishop AT, et al:
  Epstein-Barr virus infection as a complication of transplantation of a nerve allograft from a living related donor. *J Neurosurg* 2007; 106:924-928.Case report

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

  Birch R, Dunkerton M, Bonney G, Jamieson AM:
  Experience with the free vascularized ulnar nerve graft in repair of supraclavicular lesions of the brachial plexus. *Clin Orthop Relat Res* 1988; 237:96-104.

Central repair

- Central repair: reimplantation of avulsed spinal nerve-

  Birch R, Bonney G, Parry CW: *Reimplantation of avulsed spinal nerves*. *Surgical Disorder of the Peripheral Nerves*, London: Churchill Livingstone; 1998:201-207.

- Functional benefits have been observed in some cases-

  Carlstedt T, Grane P, Hallin RG, Noren G:
  Return of function after spinal cord implantation of avulsed spinal nerve roots. *Lancet* 1995; 346:1323-1325.

  Carlstedt T, Anand P, Hallin R, et al:
  Spinal nerve root repair and reimplantation of avulsed ventral roots into the spinal cord after brachial plexus injury. *J Neurosurg* 2000; 93(suppl):237-247.

  Carlstedt T: *Central Nerve Plexus Injury*. London, Imperial College Press, 2007.

  Carlstedt T, Hultgren T, Nyman T, et al:
  Cortical activity and hand function restoration in a patient after spinal cord surgery. *Nat Rev Neurol* 2009; 5:571-574.

- Should be done within 6 weeks of injury- anterior horn cells become dead after 6 weeks of avulsion- Fournier HD, Mercier P, Menei P:
  Repair of avulsed ventral nerve roots by direct ventral intraspinal implantation after brachial plexus injury. *Hand Clin* 2005; 21:109-118.

  Fournier HD, Mercier P, Menei P:
  [Spinal repair of ventral root avulsions after brachial plexus injuries: Towards new surgical strategies?]. *Neurochirurgie* 2006; 52:357-366.

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

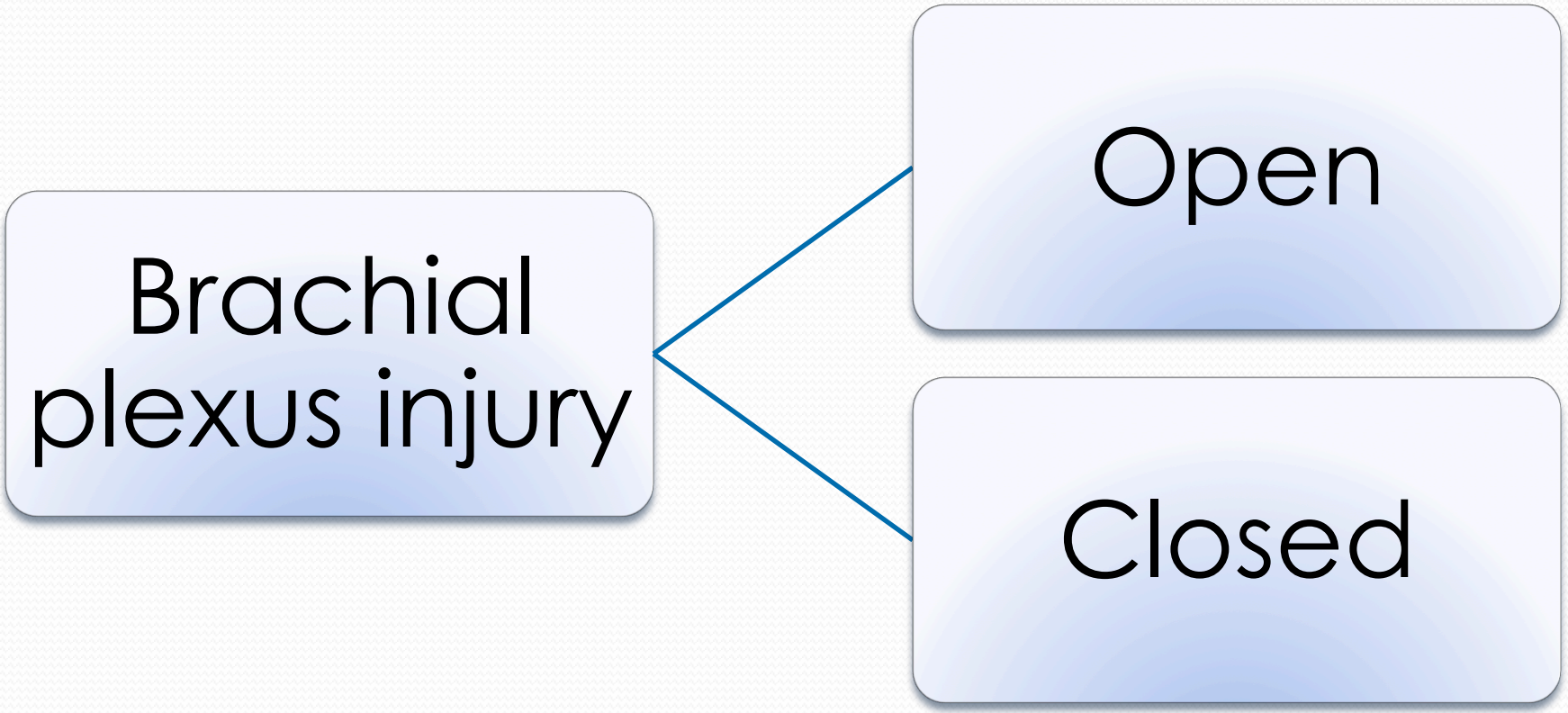
    Steindler A: Orthopaedic reconstruction work on hand and forearm. *N Y Med J* 1918; 108:1117-1119

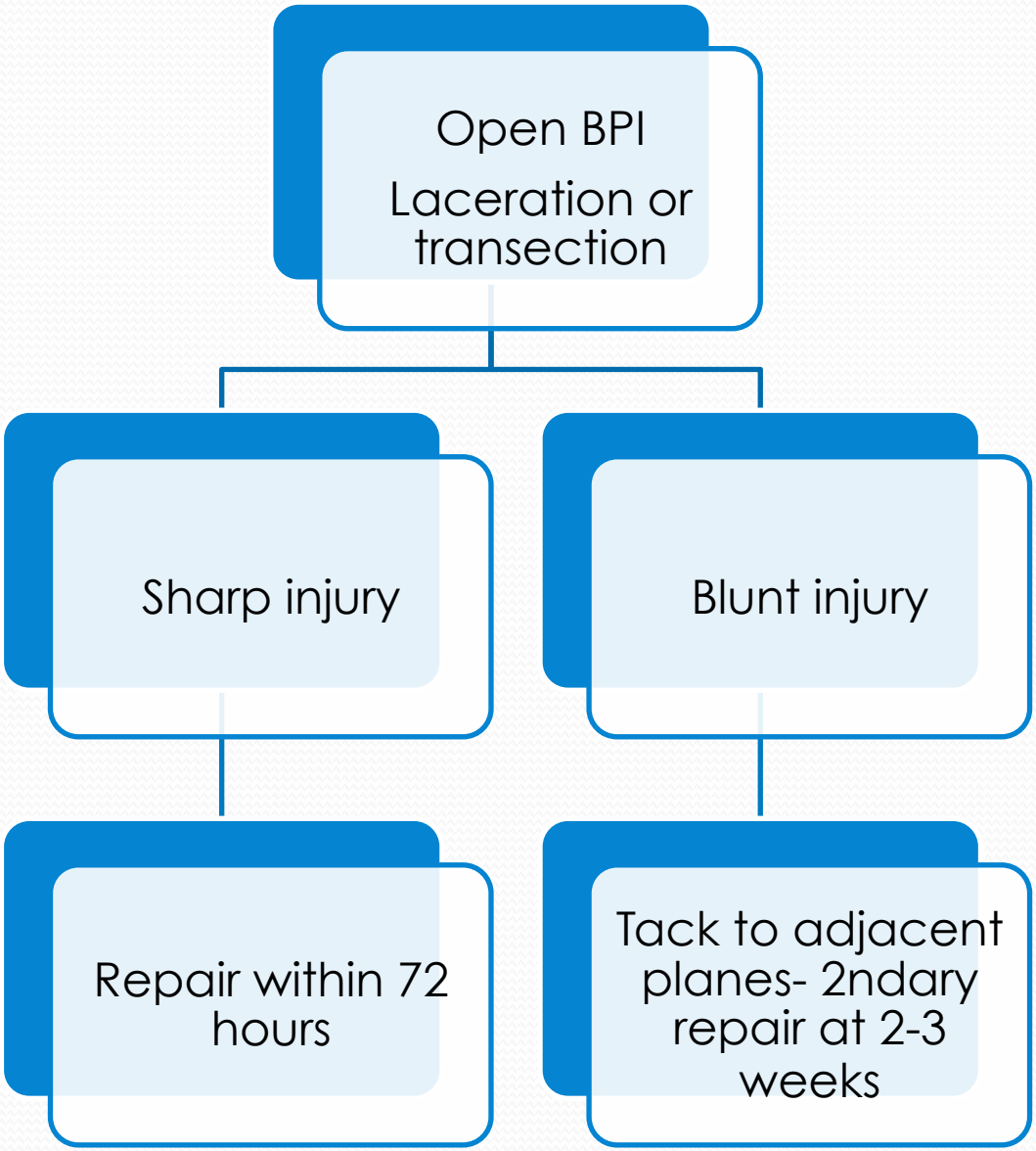
    Chen WS: Restoration of elbow flexion by modified Steindler flexorplasty. *Int Orthop* 2000; 24:43-46.
  - Pec major flexorplasty: insertion sutured to coracoid process & origin to biceps tendon
  - Wahegaonkar AL, Doi K, Hattori Y, et al: Surgical technique of pedicled bipolar pectoralis major transfer for reconstruction of elbow flexion in brachial plexus palsy. *Tech Hand Up Extrem Surg* 2008; 12:12-19
  - Lat dorsi transfer: flexorplasty with soft tissue coverage
- Wrist & hand function: PT to ECRB transfer, opponensplasty

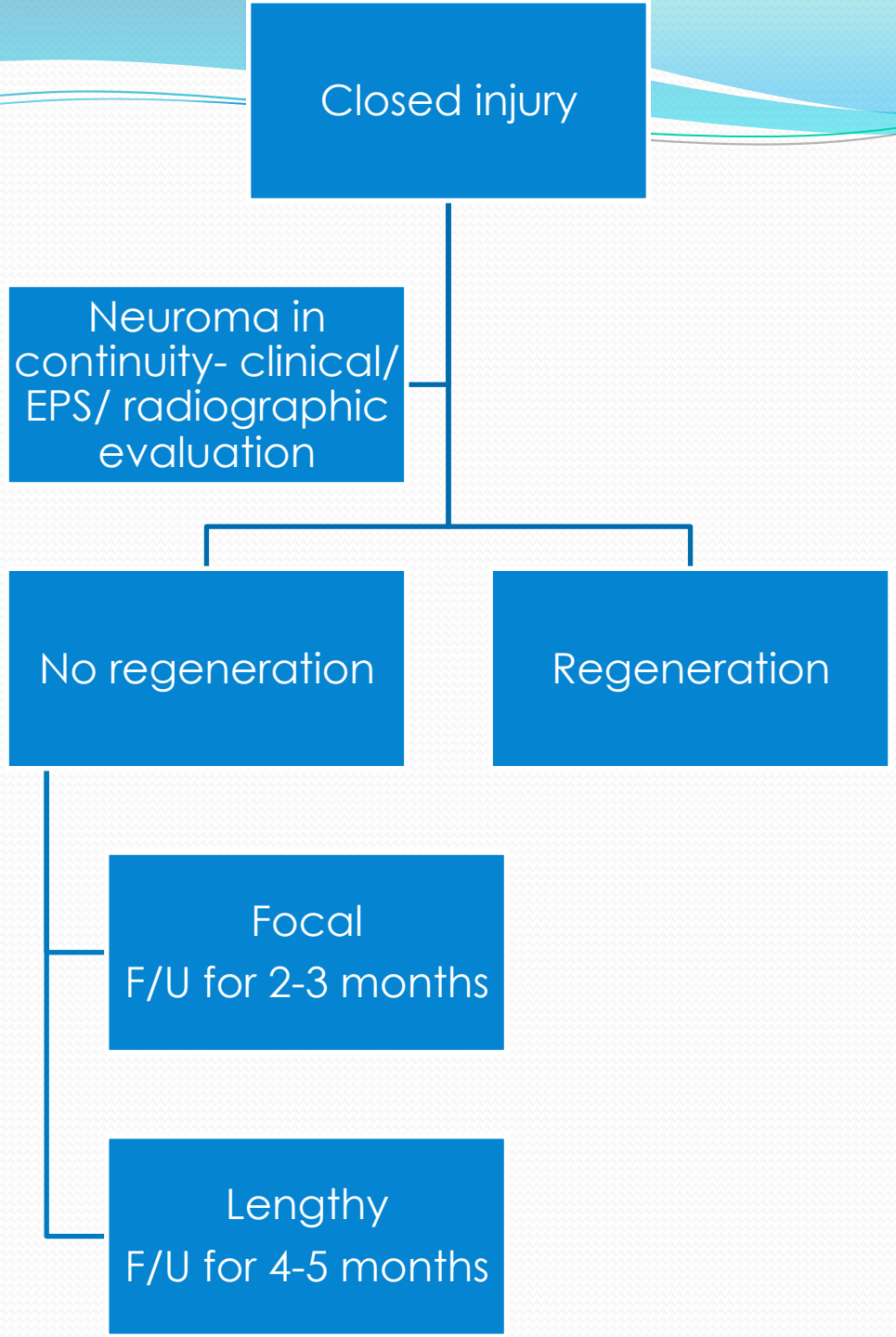
Functioning free muscle transfer

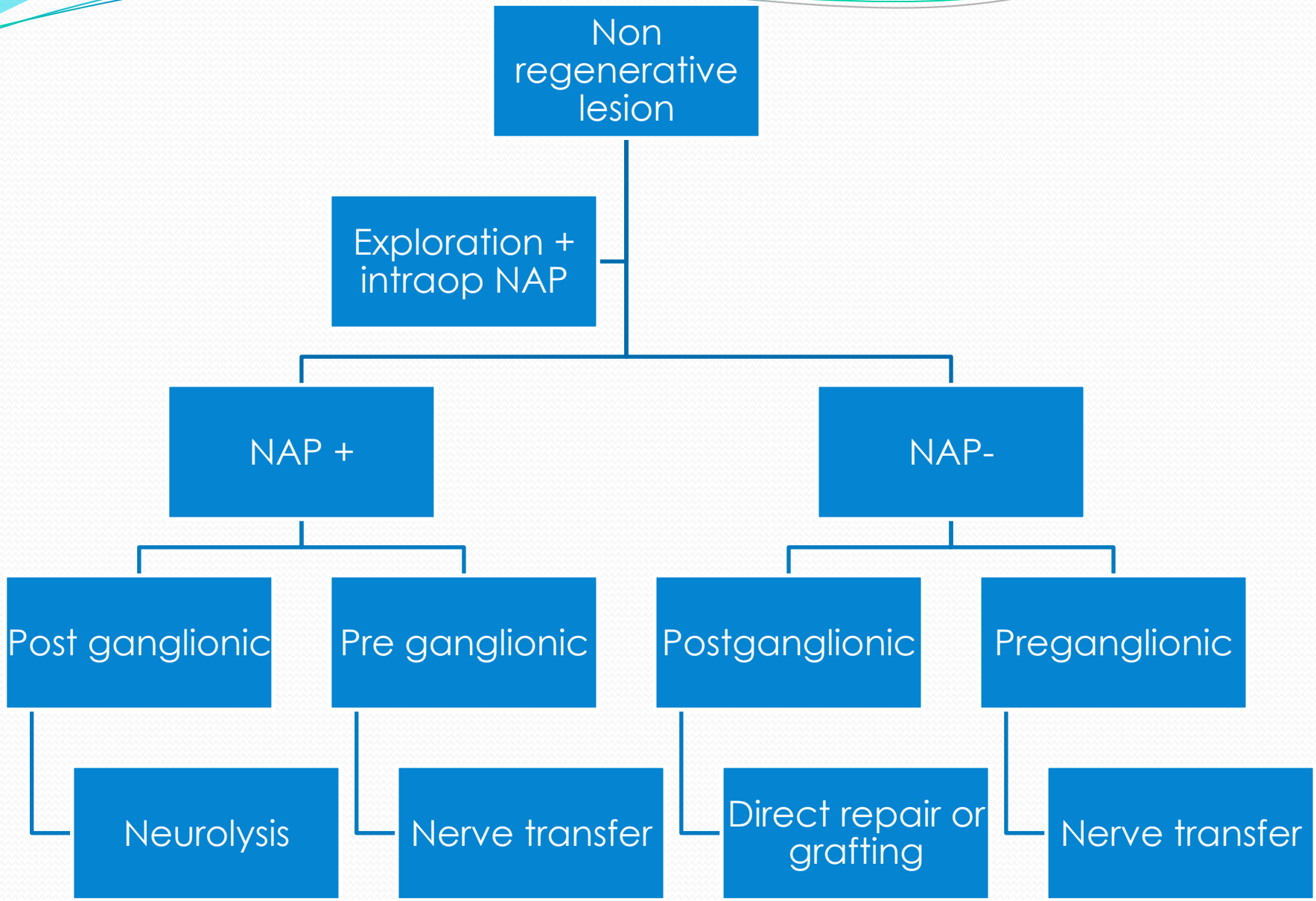
- Involves micro-neurovascular repair of a transplanted muscle
- To restore elbow flexion, shoulder abduction, elbow extension, finger flexion & extension
- Muscles used: gracilis, rectus femoris, LD, pec major, TFL, adductor longus

Special situations


Brachial plexus injury
Open
Closed


Open BPI
Laceration or transection
Sharp injury
Blunt injury
Repair within 72 hours
Tack to adjacent planes- 2ndary repair at 2-3 weeks


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


Non regenerative lesion
Exploration + intraop NAP
NAP +
NAP-
Post ganglionic
Pre ganglionic
Postganglionic
Preganglionic
Neurolysis
Nerve transfer
Direct repair or grafting
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:
  In vivo use of a nanoknife for axon microsurgery. *Neurosurgery* 2007; 61:683-691

- 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

  Pfister LA, Papaloizos M, Merkle HP, Gander B:
  Nerve conduits and growth factor delivery in peripheral nerve repair. *J Peripher Nerv Syst* 2007; 12:65-82

- Role of stem cells: under investigation

  BOOCKVAR, JOHN A. Hair Follicle Stem Cells Support Repair of Severed Nerves. NeurosPeripheral Surgery: February 2006 - Volume 58 - Issue 2 - p N9

AIIMS data

- Since 1995 to2002 , 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