# Functional Peripheral Nerve Surgery

**Bunpot Sitthinamsuwan, M.D., M.Sc., Sarun Nunta-aree, M.D., Ph.D.**

*Department of Surgery, Faculty of Medicine Siriraj Hospital, Mahidol University, Bangkok 10700, Thailand.*

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**Background**

Peripheral nerve surgery mostly focuses on nerve repair or neurotization for nerve injuries, decompression for entrapment neuropathies, and removal of peripheral nerve tumors.[1,2] Another category of peripheral nerve surgery called "functional peripheral nerve surgery" is proposed, the definition of which has not been clearly delineated. In our opinion, functional peripheral nerve surgery involves surgical procedures upon the peripheral nerves which do not have structural lesions (trauma, entrapment or tumor). It emphasizes in the treatment of focal dystonia, focal spasticity, intractable pain and restoration of innervated organ function. The procedures are primarily composed of selective peripheral denervation (SPD) for cervical dystonia, selective peripheral neurotomy (SPN) for focal spasticity, peripheral nerve stimulation (PNS) for chronic intractable pain and functional pacing of the peripheral nerve for restoration of the organ function, particularly the phrenic nerve stimulation for diaphragmatic pacing. This article reviews the current state of the art on common operative procedures and clinical benefits of this surgical field - functional peripheral nerve surgery.

## Selective peripheral denervation (SPD) for cervical dystonia

Cervical dystonia is the most common form of focal dystonia.[3] The condition is commonly categorized into torticollis, retrocollis, anterocollis, laterocollis and any combination of them. The involved neck muscles vary depending on the pattern of cervical dystonia (Fig 1). Therapeutic managements of cervical dystonia include oral medications, botulinum toxin injection and neurosurgical treatments (ablative brain lesioning, deep brain stimulation or SPD).[3,4] However, some patients require combined treatments for better outcomes.

A good candidate for SPD is one with cervical dystonia with botulinum toxin resistance.[5-7] SPD is generally recommended for patients with intractable cervical dystonia associated with significant disability or pain.[8] Furthermore, it can be considered as a primary treatment for the severe cases. The denervating procedures on the neck muscles depend on the patterns of cervical dystonia. The commonly used SPD for spasmodic torticollis is Bertrand's operation. The operation

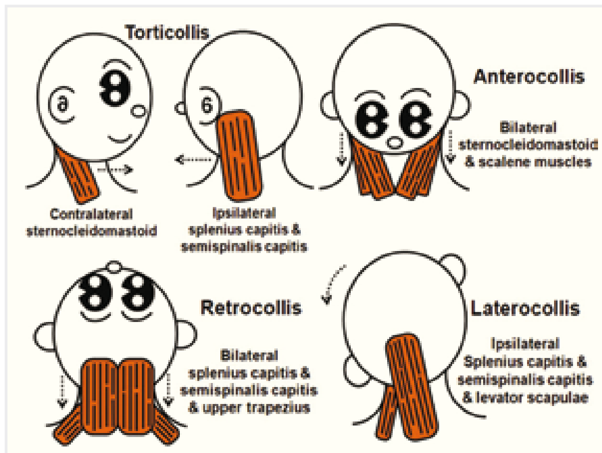


**Fig 1.** The patterns of cervical dystonia and corresponding neck muscles.

comprises of an ipsilateral posterior ramisectomy of the extradural C1-C6 spinal nerves supplying the posterior neck muscles (Fig 2A) with contralateral selective denervation of the accessory nerve supplying sternocleidomastoid (SCM).[9,10] An important disadvantage of this operation is postoperative sensory loss in the ipsilateral C2 dermatome. Therefore, Taira et al. modified Bertrand's operation to Taira's method for avoidance of the sensory loss. Taira's method includes ipsilateral intradural C1-C2 ventral rhizotomy which can preserve the C2 dorsal (sensory) spinal nerve with ipsilateral posterior ramisectomy of the extradural C3-C6 spinal nerves and contralateral peripheral sectioning of the motor branches of the accessory nerve. The C2 dysesthesia and intraoperative blood loss are significantly reduced with this novel denervation procedure.[11,12] A combination of SPD and neck muscle resection is also noted.[13,14]

The surgical treatment of isolated laterocollis is selective denervation of the levator scapulae muscle (LSM) which is supplied by the anterior branches of the C2-C5 spinal nerve.[15,16] Cohen-Gadol and colleagues mentioned about selective denervation of the ipsilateral accessory nerve supplying SCM in laterocollic cervical dystonia.[16] Bilateral partial denervation of the upper part

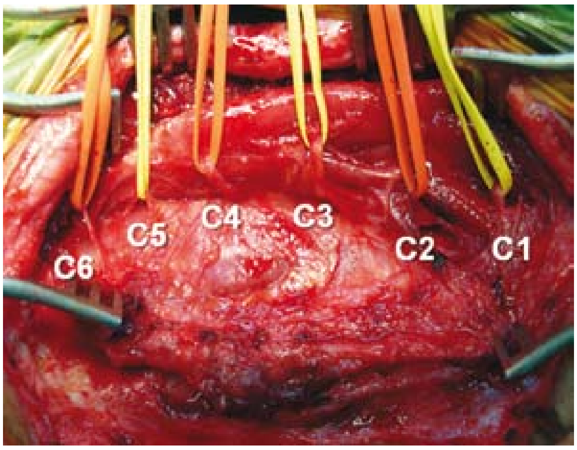


**Fig 2.** An operative exposure of ipsilateral C1-C6 posterior rami (C1-C6) in SPD for cervical dystonia.

of the trapezius, splenius capitis, semispinalis capitis and semispinal cervicis are usually performed in patients with retrocollis.[17]

Anterocollis is often managed surgically by deep brain stimulation rather than SPD of the bilateral anterior neck muscles because of the risk to the latter for anterior neck muscle weakness and swallowing dysfunction.

Most series of SPD for cervical dystonia exhibited good to excellent results.[6,7,9,13-16,18] The major surgical-related complication of SPD was sensory loss or dysesthesia in the denervated dermatome.[15,16] There was neither significant swallowing dysfunction nor weakness of the neck muscles after the operation.[7,19]

## Selective peripheral neurotomy (SPN) for spasticity

Spasticity is an indicative hallmark of central nervous system lesions.[20] The spasticity is commonly found in patients who have brain or spinal cord lesions, such as traumatic brain or spinal cord injury. Importantly, harmful spasticity is a major problem for rehabilitation and care of patients. Moreover, orthopedic complications, including contracture, are common sequelae of severe spasticity which increase difficulty in rehabilitation.

There are various treatments for spasticity helpful in the management of these patients. For example, oral antispasmodic drugs, botulinum toxin injection and neurosurgical procedures, especially SPN, may be utilized.

SPN of the limbs has been an alternative therapeutic option for patients with severe intractable spasticity since the late 19th century.[21-25] SPN is selective partial resection of fascicles in one or more motor branches of the peripheral nerves supplying an excessively spastic muscle.[26] Neurotomy affects both afferent proprioceptive fibers projecting from spastic muscles to the spinal cord and the efferent motor fibers leading from the spinal motor neurons to the muscles.[26-28] The disruption of the spinal reflex arch results in a rebalance of muscle tone between agonist and antagonist muscles.[27] During the operation, the motor branches are identified by surgical anatomy and intraoperative mapping with electrical nerve stimulation.[26-31] The latter is essential in order to distinguish between the actual motor and sensory nerves. Electrical stimulation of the motor branch elicits contraction of a corresponding muscle, whereas stimulation of the sensory branch results in an absence of the motor response. Because the diffusion of electrical current to a neighboring motor branch may lead to a misinterpretation of muscle contraction one must be cautious.[26-28] The resection of the nerve is only performed on the motor branches (Fig 3). The mixed major nerve trunk and sensory branches are entirely preserved to avoid deafferenting pain.[26,27]

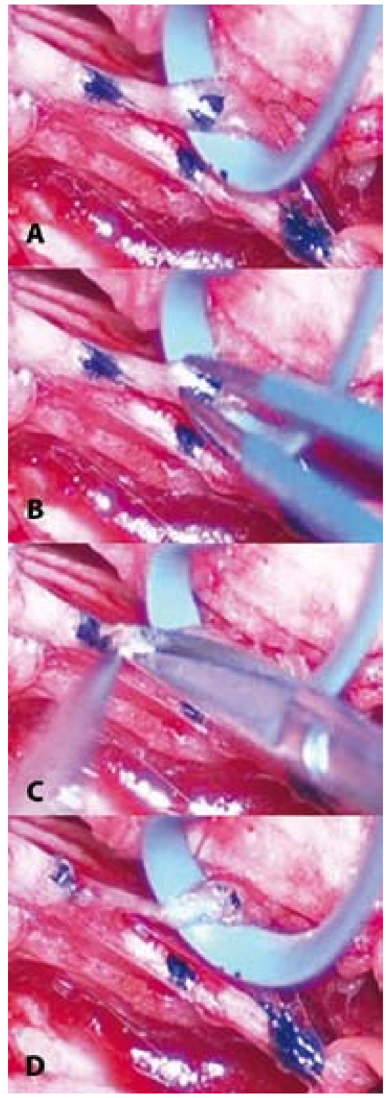


**Fig 3.** (A) Microsurgical exposure of motor branches. (B) Intraoperative electrical nerve stimulation with visible muscle contraction reassures that the nerve is a motor branch before a neurotomy. (C) The isolated motor branch is partially being sectioned longitudinally with microscissors for 5 to 10 mm in length represented by a distance between the blue dots on the same nerve. Proportion of the partial nerve resection (50-80%) depends on the severity of preoperative spasticity. (D) After a neurotomy, a residual nerve fascicle is left in its place.

The main indication for SPN is refractory focal spasticity. However, SPN can be frequently used for treatment of either multifocal or regional spasticity which does not respond to non-operative management. Good candidates should have spasticity without orthopedic disorders, particularly muscle shortening or contracture.[26,27] However, spastic patients who have associated contracture or muscle shortening should be treated with

**TABLE 1.** The patterns of limb spasticity, operative procedures, involved motor branches, and associated muscles.[26-31,33-35]

| Patterns | Procedures | Motor branches | Associated muscles |
|---|---|---|---|
| Spastic shoulder internal rotation and adduction | Pectoral neurotomy<br>Teres major neurotomy | Lateral pectoral nerve<br>Nerve to teres major | Pectoralis major<br>Teres major |
| Spastic elbow flexion | Musculocutaneous neurotomy | Nerve to biceps brachii<br>Nerve to brachialis | Biceps brachii<br>Brachialis |
| Spastic wrist and fingers flexion | Ulnar neurotomy<br>Median neurotomy | Nerve to FCU<br>Nerve to 3rd-4th FDP<br>Nerve to PT<br>Nerve to PL<br>Nerve to FCR<br>Nerve to FDS<br>AIN | FCU<br>3rd-4th FDP<br>PT<br>PL<br>FCR<br>FDS<br>FPL & 1st-2nd FDP |
| Spastic hip adduction | Obturator neurotomy | Anterior division of the obturator nerve | AL, AB, Gracilis |
| Spastic knee flexion | Sciatic neurotomy | Nerve to hamstring muscles | Biceps femoris<br>Semimembranosus<br>Semitendinosus |
| Spastic knee extension | Femoral neurotomy | Nerve to rectus femoris<br>Nerve to vastus intermedius | Rectus femoris<br>Vastus intermedius |
| Spastic ankle plantar flexion or spastic equinus foot | Tibial neurotomy | Nerve to MG<br>Nerve to LG<br>Nerve to soleus | MG<br>LG<br>Soleus |

FCU; flexor carpi ulnaris, FDP; flexor digitorum profundus, PT; pronator teres, PL; palmaris longus, FCR; flexor carpi radialis, FDS; flexor digitorum superficialis, AIN; anterior interosseous nerve, FPL; flexor pollicis longus, AL; adductor longus, AB; adductor brevis, MG; medial gastrocnemius, LG; lateral gastrocnemius

combined SPN and orthopedic procedures.[28-31] The operations for upper extremity spasticity consist of pectoral neurotomy, teres major neurotomy, musculocutaneous neurotomy, median neurotomy and ulnar neurotomy,[26,28-31] whereas, obturator neurotomy, sciatic neurotomy, tibial neurotomy, and femoral neurotomy are SPN for lower limb spasticity.[26,27,32,33] The patterns of spasticity, types of surgery, involved motor branches and associated muscles are indicated in Table 1.

Selective tibial neurotomy is a popular surgical procedure in SPN. It is commonly indicated for ankle spasticity presenting with spastic equinovarus foot. The various types of incision can be made on the popliteal fossa (Fig 4A and 4B). The tibial nerve trunk and its branches should be clearly identified. The motor branches include nerves to the medial gastrocnemius (MG), lateral gastrocnemius (LG) and soleus muscles (Fig 4C). The medial sural branch is a sensory branch in this region which should be excluded from the neurotomy.[26,27] The motor branches are selectively denervated depending on the patterns of ankle spasticity. Post-operatively, the majority of the patients develop marked improvement in plantigrade, gait and electrophysiologic studies as a result of eliminated ankle spasticity (Fig 5).[32,34,36-41]

The overall results of SPN in the treatment of focal spasticity have been fairly good.[29-31,34-38,40-41] Complications are trivial and rarely occur, including surgical wound infection, local hematoma, transient sensory impairment, transient deafferenting pain and scarring.[26-28,31]

## Peripheral nerve stimulation (PNS) for chronic pain

Examples of electrical stimulation of the peripheral nerve are vagus nerve stimulation for intractable epilepsy and PNS for chronic pain disorders.[42] PNS has been introduced for intractable pain since the 1970s.[43,44] Thereafter, its devices have been continuously developed to improve the therapeutic outcomes.[45,46]

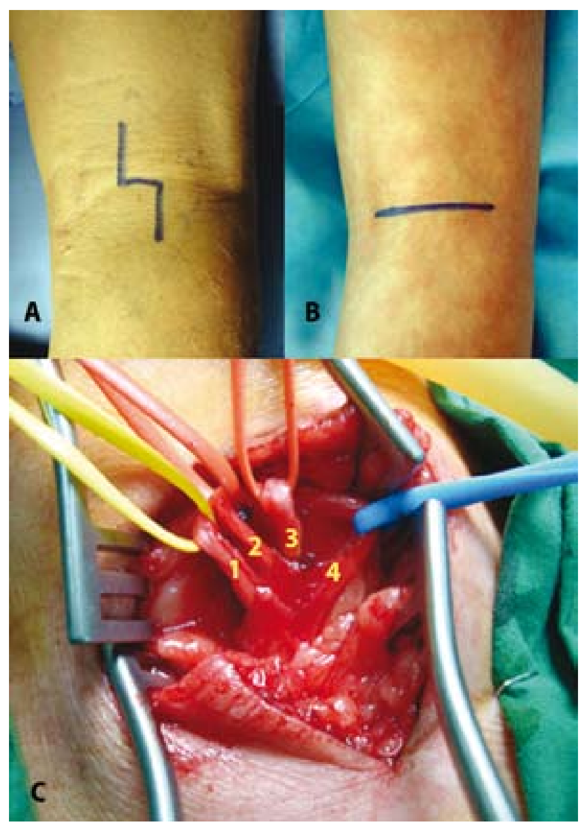


**Fig 4.** Selective tibial neurotomy. (A) A classic vertical incision on the skin of the popliteal fossa. (B) An alternative transverse incision results in a better cosmetic outcome. (C) Operative exposure of the branches of the tibial nerve in the popliteal region, 1; nerve to lateral gastrocnemius (LG), 2; nerve to soleus, 3; nerve to medial gastrocnemius (MG), 4; medial sural branch of the tibial nerve.


**Fig 5.** Comparison of gait before and after selective tibial neurotomy for spastic equinovarus foot. (A) Pre-operative gait shows spastic equinovarus of the right ankle (black arrows). (B) Post-operative gait reveals a complete plantigrade of the right foot during the stance (white arrows).

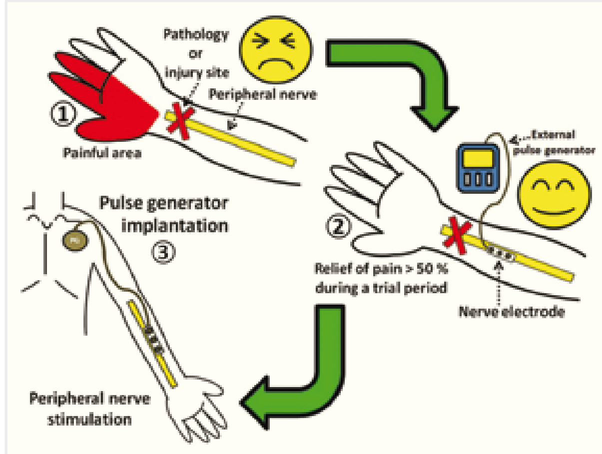


**Fig 6.** A representative diagram of peripheral nerve stimulation for the treatment of chronic neuropathic pain. (1) A painful area (red color) is distal to the pathology or injury site on a nerve. (2) The first stage operation; an electrode is placed on the nerve and connected to an external pulse generator. During a trial period, more than fifty percent of pain relief suggests a good candidate for the next operative session. (3) The second stage procedure; a pulse generator (PG) is permanently implanted in a subcutaneous pocket. The infraclavicular region is the most common location for the implantation.

A general indication of PNS is severe chronic neuropathic pain refractory to non-operative management. The indicated pain disorders are traumatic neuropathic pain, complex regional pain syndrome (CPRS), iatrogenic pain following injection or surgery, entrapment neuropathy, tumor and pain in the head and neck region.[43,47-51] The latter is comprised of occipital neuralgia, transformed migraine, cluster headache, cervicogenic pain, chronic daily headache and neuropathic facial pain. Most head and neck pain can be effectively treated by using occipital nerve, supraorbital nerve, or infraorbital nerve stimulation.[42,52-54]

Principally, the procedure of PNS is divided into two operative stages.[42,43,50,51,53,54] The first stage is a placement of an electrode on a selected nerve. The electrode is situated on the targeted nerve proximal to the pathology or injury site relating to painful distribution of the nerve.[49] It is temporarily connected to an external pulse generator adjusted by the patient during a trial period. The trial period of stimulation is varied from 2 to 15 days depending on clinical responses.[49,50,51,53] The responses are mainly assessed by reduction in pain score and decreased use of analgesics. Reduction of pain by at least 50% or more indicates a good candidate for long-term use of PNS.[50,54] The second stage is an implantation of a permanent pulse generator for chronic PNS.[42,43,50,51,53,54] High-frequency stimulation of the peripheral nerve theoretically interrupts abnormal nerve conduction of small nociceptive afferent fibers (Aδ and C fibers). Concurrent stimulation of large nociceptive afferent fibers (Aß fibers) results in modulation of the nociceptive pathway in the posterior horn of the spinal cord, or in the supraspinal regions (gate control theory).[54] A representative diagram of PNS is summarized in Fig 6.

Good outcomes (more than 50% of pain relief) of PNS varied from 43-70%.[43,47-51,53,55] The reported complications included hardware infection, broken lead, hardware disconnection, undesired motor effect on an adjacent muscle and nerve ischemia.[43,48-50]

## Functional peripheral nerve pacing and phrenic nerve stimulation for diaphragmatic pacing

Phrenic nerve stimulation for restoration of the function of the diaphragm and sacral nerve stimulation for the neuropathic bladder are most commonly mentioned among functional pacing of the peripheral nerve. Phrenic nerve stimulation for diaphragmatic pacing has been proposed in humans since the 1950s.[56] A major indication of the procedure is central hypoventilation syndrome caused by lesions in the central nervous system which mainly involve the high cervical cord or brainstem.[57,58] A therapeutic goal of the operation is either spontaneous breathing by the patients without ventilatory support or reduction in utilization of a ventilator.[59-61]

The principle of the operation appears similar to that of the peripheral nerve stimulation. The devices consist of electrodes and pulse generator(s). Exploration of the phrenic nerve can be done either in the posterior triangle of the neck or the thorax.[60,62-65] Intraoperative electrical stimulation of the phrenic nerve results in contraction of the ipsilateral diaphragm. An electrode is placed on the phrenic nerve on one side. The operation is conducted bilaterally. The electrode on each side is connected to the same or separate pulse generators. During the time when the one-sided pulse generator is


**Fig 7.** Real-time fluoroscopy of the diaphragm. (A) Normal position of the both sides of the diaphragm is demonstrated during turning off both-sided pulse generator. (B) During a turning on of the right-sided pulse generator, a downward movement of the same side of the diaphragm is seen (dotted arrow). (C) The left pulse generator is turned on, showing a movement of the left-sided diaphragm (dotted arrow).

turned on, the diaphragm on the same side is simultaneously moving, and vice versa (Fig 7).

Recently, the spinal cord stimulator which has been used as a modality in the treatment of chronic pain has been adapted for phrenic nerve stimulation with good long-term outcomes.[65,66] Many case reports and case series also revealed good results by either reduced respirator use or absolute independence from respirator.[57-63]

## CONCLUSION

The functional peripheral nerve surgery is a novel category of operative procedures on the peripheral nerve. The surgery aims to modulate various neurological disorders, including focal dystonia, spasticity and chronic pain. Additionally, it is beneficial in the restoration of the target organ function, especially the diaphragm in respiratory paralysis and urinary bladder in neuropathic bladder. The future trend of functional surgery of the peripheral nerve becomes increasingly significant in the new era of neurosurgical practice.

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