Intratruncal Variability of the Thoracodorsal Nerve: Anatomical Research

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Abstract

Thoracodorsal nerve (TDN) injuries not infrequently occur in the setting of brachial plexus injuries from various etiologies. On the other hand, the TDN may be spared even in severe brachial plexus lesions, allowing it to serve as a graft for other nerve lesions aimed at maintaining upper limb function. The aim of the present study was to investigate the types of topography of the thoracodorsal nerve within the trunk from the latissimus dorsi muscle to the spinal cord and to develop a technique for intraoperative identification of nerve fiber bundles.

On 105 male and female cadavers aged 40 to 97 years, 121 brachial plexus and thoracodorsal nerve specimens were dissected macromicroscopically intraneurally from the latissimus dorsi muscle to the spinal cord.

The thoracodorsal nerve is a mixed nerve consisting of 1-3 thin and soft bundles of sensory fibers and one thick and dense bundle of motor nerve fibers. The number of sensory bundles ranges from 1 to 3, and the motor bundle is one in all cases. As for thickness and density, the sensitive bundles are thinner and denser than the motor ones. Depending on the relationship and topography: in the thoracodorsal nerve, the motor bundle is located posteriorly and the sensory ones anteriorly in 98.3% of the cases; in the posterior bundle of the brachial plexus, the fiber bundles are in the posterior inferior part in 89%. The nerve fiber bundles are also located in the posterior-inferior part of the middle and superior trunks, in the posterior-superior part - of the inferior trunk, with the motor bundle located lower and the sensory bundle higher in 55.3% of the cases and vice versa in 38.0%; in the roots of the brachial plexus, in 98.3% of the cases, the motor bundles are in the posterior superior part and the sensory bundles in the posterior inferior part.

The thoracodorsal nerve is mixed and consists of sensory and motor bundles with a clear posterior localization throughout from the widest muscle of the back to the spinal cord. Has been developed a method of intra-trunk identification of sensitive and motor bundles which is based on determining their number, thickness, density, relationship, and localization. The obtained data can be used in intraoperative diagnosis of thoracodorsal nerve bundles and fascicular reconstruction of damaged nerves of the brachial plexus.

Clinical article (J Int Dent Med Res 2023; 16(1): 447-454)

Keywords: Thoracodorsal nerve; intra-trunk topography; sensitive bundles; motor bundles.

Received date: 27 September 2022 **Accept date:** 22 October 2023

Introduction

In connection with the development of new neurovascular technologies, such as dissection[1,2,3,4], neurotization[5,6], auto transplantation[7,8,9] and stitching[10,11,12], work has been done on the identification of sensory and motor neurons, variants of their location in the whole nerve[13,14]. The complexity of solving this problem lies in the fact that only in the distal part of mixed nerves there are areas where the bundles are isolated and can be identified, while in the proximal part sensory and motor nerve fibers are scattered throughout the cross-section of the nerve[15,16]. The difficulty in identification is

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also related to the fact that after the injury, fascicular atrophy of the nerve is observed, which progresses and affects 60-70% of the nerve fibers in the first three months. At the same time, fascicular atrophy is less pronounced in the area of the nerve where the bundles are clearly separated by the intraneural epineurium[17,18]. In this regard, in proximal nerve lesions, where many mixed nerve fibers are present and identification is difficult, epineural repair is preferable, whereas in distal sections, fascicular (perineural) plastic is more appropriate[19,20,21].

However, to restore the function of the distal portion of the nerve, accurate intraoperative identification is required because the bundles are formed only a few centimeters before exiting the main trunk[22,23].

Despite significant advances in microsurgical treatment of nerves, the various techniques that allow rapid and accurate identification of motor and sensory fiber bundles during surgery and their localization have serious drawbacks[18, 24]. Currently, there are histochemical, electrophysiological, instrumental, and anatomical methods for identifying nerve fibers within a nerve[14,22].

Histochemical methods are used because the activity of choline acetylase and choline acetyltransferase is higher in motor nerve bundles than in sensory ones[25,26]. The enzymatic activity method can also detect sympathetic postganglionic fibers[27]. Detection of carbonic anhydrase has been proposed to identify sensory neurons[28,29]. However, histochemical methods inaccurately detect sensory and motor fibers, require a long incubation time (50-80 minutes), and do not allow diagnosis 5 days after injury[30,31]. Immunohistochemical methods, including dynamic observation of specific proteins of sensory and motor nerve bundles (proteomics), as well as molecular fluorescent labeling with quantum dots performed in experimental animals, show promising results but require long-term adaptation for use in patients[14,32,33].

Electrophysiological methods such as electrical stimulation, central motor evoked potentials, H-reflex and M-wave showed good results in differentiating sensory and motor bundles in peripheral nerves intraoperatively in patients and in animal experiments[34,35]. However, these methods are very sensitive to many factors and are not accurate enough, are uncomfortable for patients, require awakening from anesthesia, local anesthesia, or the method cannot be applied to intact nerve trunks in situ and late injuries[14,24,36,37].

Instrumental methods include a wide range of modern investigations: Spectroscopy, ultrasound, magnetic resonance imaging[38]. The positive results of spectroscopy and cluster analysis methods cannot be readily applied during surgery due to the extensive equipment and complex calculations required[39,40].

Ultrasound and MRI imaging techniques are making progress but do not yet allow assessment of the fine structure of the nerves. Diffusion tensor MRI also does not provide accurate information about the features of the intranerval structure due to its small size and course, geometric distortions, and artifacts[41,42,43,44]. Numerous anatomical studies have contributed greatly to the identification of fascicular structure and underlie all methods developed[11,15,16,20,45]. Data from various sources indicate somatotopic grouping of nerve fibers in strictly localized areas (up to 21 cm long) of the distal parts of the nerve[12,46,47], and sensory bundles are much denser than motor bundles[21]. However, there is no appreciable information on the fascicular structure of the proximal nerve bundle. Therefore, nerve morphology alone cannot effectively help in identifying nerve bundles[14,24,33].

Considering that the above results are based on the study of long mixed nerves of the upper and lower extremities, we performed a study of the intratruncal structure of the thoracodorsal nerve, which is a "short" nerve of the brachial plexus. Only a limited number of papers have been devoted to the intratruncal structure of the thoracodorsal nerve. The thoracodorsal nerve is purely motor, the number of myelinated fibers ranges from 1530 to 2470 axons[48], and more than 52% of motor fibers are in its posterior part[49]. The thoracodorsal nerve consists of 2-4 bundles, and the average number of myelinated nerve fibers in the branches is 974-1843 axons[50,51]. Immunofluorescence method detected 6904 (±3070) axons in the thoracodorsal nerve, of which 927 (±79) are motor axons and 5977 (±3066) are sensory axons[29].

Consequently, many complex and inaccurate identification methods force surgeons to rely mainly on their own experience to evaluate the nerve fibers in the stump of an

injured nerve. Therefore, there is a great need for new simple and more efficient methods to identify sensory and motor fiber bundles along the entire length of the nerve[24,29].

With this background, the aim of the present study was to analyze different types of topography of the thoracodorsal nerve in its course from the latissimus dorsi muscle to the spinal cord and to develop a technique for intraoperative identification of nerve fiber bundles.

Materials and methods

The study was conducted in the Department of Cadaveric Examinations of the Krasnoyarsk Regional Bureau of Forensic Medical Examinations on 121 specimens of the brachial plexus and thoracodorsal nerve from 105 male and female cadavers aged 40 to 97 years. All cadavers were examined on the right side; in 16 cadavers, both sides, right and left, were examined simultaneously. All subjects examined had died recently; the time between death and dissection ranged from 4 - 20 hours. The cause of death in all cases was general somatic disease, with no injuries to the head, neck, upper limbs, or chest. The study was approved by the local ethics committee of KrasSMU (Protocol No. 91, September 11, 2018). The study of variants of intratrunkal topography of the thoracodorsal nerve was performed by macroscopic slice-by-slice anatomical and macro microscopic intratrunkal preparation. In the first phase, a slice-by-slice anatomic preparation was performed with isolation of the spinal cord, radicular filaments, anterior (motor) and posterior (sensory) roots, anterior branches of spinal nerves, roots, trunks, divisions, and bundles, and the thoracodorsal nerve.

The isolated brachial plexus preparation was placed in a 10% solution of neutral formalin for 1-3 days, which is most used and does not affect the structure of proteins[51]. The preparation was then fixed in a 2% acetic acid solution until the end of the preparation. The choice of acetic acid is related to its properties of counteracting the shrinkage effect and dissolution of the extra- and intraneural epineurium collagen[12, 52, 53]. The choice of concentration and duration of fixation in acetic acid is due to the need to isolate the nerve fiber bundles a traumatically from the dense structures of the brachial plexus.

In the second step, local intratubular macro-microscopic dissection of the thoracodorsal nerve with exposure of nerve fiber bundles along the length from the latissimus dorsi muscle to the posterior bundle of the brachial plexus was performed using microsurgical instrumentation, Carl Zeiss ×2.5 binocular loupe, and MBS-10 ×8 and ×16 stereoscopic loupe. The third step was complete macro-microscopic intratruncal dissection of nerve fiber bundles of the thoracic nerve along the entire length of the brachial plexus to the spinal cord. Dissection of the nerves was performed under visual control by opening the epineurium and separating the bundles with extreme care to avoid damaging their perineurium. Special attention was paid to the roots of the spinal cord through which the selected bundles of the thoracic nerve pass, which made it possible to determine their functional affiliation: by the anterior - motor, posterior - sensory.

All identified features of the intrastematic structure of the thoracic nerve were entered into the MS Excel 10.0 program, and the database was analyzed using the Statistica for Windows 10.0 program.

Results

Macro microscopic intratrunk preparation revealed that the thoracodorsal nerve is a mixed nerve consisting of a varying number (1-3) of sensory bundles and one motor bundle (Fig. 1).

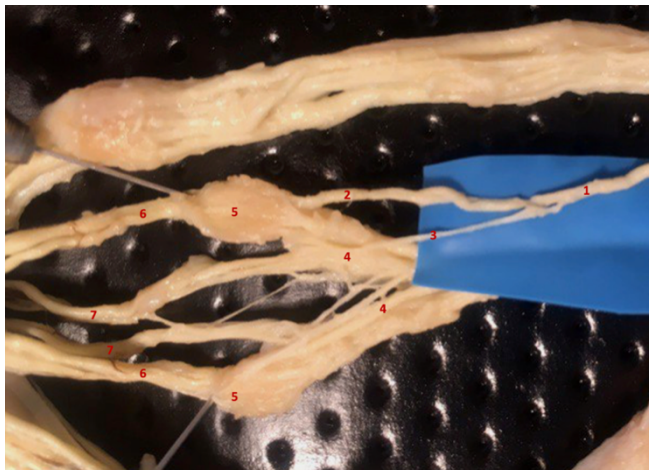

Figure 1. Macro preparation of the formation of the sensitive and motor bundles of the thoracodorsal nerve, their topography as part of the spinal nerve C7 (*longitudinally divided into two halves*), anterior and posterior roots

(*longitudinally divided into two halves*), of the spinal cord (dorsal view) of the brachial plexus of a 79-year-old woman. 1 - thoracodorsal nerve; 2 – sensory bundle; 3 - motor bundle; 4 - spinal nerve (C7); 5 - ganglion sensorium nervi spinalis; 6 - radix posterior; 7 - radix anterior.

Thus, the thoracodorsal nerve consists of two bundles in 76% (92 plexuses) of cases, three in 21.5% (26 plexuses), one in 1.7% (2 plexuses), and four in 0.8% (1 plexus). Sensitive bundles were found to be significantly (p=0.008) thinner than motor 0.71 [0.5; 0.83] mm with a thickness of 0.58 [0.33; 0.66] mm. When touched with microsurgical instruments, sensitive bundles were softer and motor bundles were harder/tighter. The smaller the thickness and softness of the sensory bundles, the greater the thickness and density of the motor bundles, which were preserved to the spinal cord. In a two-bundle structure of the thoracodorsal nerve, one thin and soft bundle of sensitive fibers is identifiable and the other thick and dense motor. In a three-bundle structure, one thick and dense bundle is motor and the other two thin and soft are sensitive. In a four-bundle structure, one thick and dense motor bundle and three thin and soft sensitive ones are identifiable. In a single-beam structure of the thoracodorsal nerve, the nerve fibers are intertwined, so that it is not possible to distinguish motor and sensitive portions.

The isolated bundles in the thoracodorsal nerve were not intertwined in 98.3% of cases and were isolated from each other in strictly localized areas. Thus, in 90.9% (110 plexuses) of cases, the motor bundle was in the posterolateral part of the thoracodorsal nerve and the sensory bundle in the anteromedial. In 7.4% (9 plexuses) of cases, the motor nerve fiber bundle was in the posteromedial portion and the sensory bundle in the anterolateral portion. In 1.7% (2 plexuses) of cases, sensory and motor nerve fibers were intertwined, making it impossible to isolate the bundles and determine their location.

Distally, 1 cm before the division of the thoracodorsal nerve into its extramuscular branches, the nerve fibers of the sensory and motor bundles intertwine and branch into different branches. In the branches, the intertwining of the nerve fibers continues 1 cm from the branching point, and then separate sensory and motor bundles are again formed, but of smaller diameter.

In the posterior bundle of the brachial plexus, the motor and sensory bundles of the thoracodorsal nerve are localized in the posterior inferior part in 89.2% (108 plexuses) of cases, in the anteroinferior in 5.8% (7 plexuses), and in the middle posterior in 5.0% (6 plexuses) (Fig. 2).

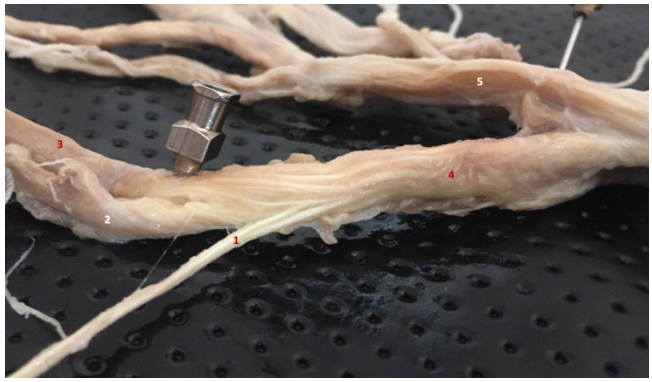

Figure 2. Macro preparation of the thoracodorsal nerve as part of the posterior bundle (posteroinferior surface) of the brachial plexus of a 59-year-old man. 1 - Thoracodorsal nerve (2-bundle structure); 2 - axillary nerve; 3 - radial nerve; 4 - posterior fasciculus; 5 - medial fasciculus.

The first variant of posterior-inferior localization and the third posterior-medial localization are found when the thoracodorsal nerve emerges from the posterior bundle. The second variant of anterior-inferior localization is noted when the thoracodorsal nerve arises from the axillary nerve. The relationship between sensory and motor portions in the posterior bundle of the brachial plexus is stable: in 98.3% (119 plexuses) of cases, the motor bundle is located inferiorly, and the sensory portions are located superiorly. In 2 plexuses (1.7%), it was not possible to determine the mutual localization of the bundles because of the intertwining of the nerve fibers.

In the brachial plexus trunks, the sensory and motor bundles of the thoracodorsal nerve are unevenly distributed. More often, in 43% (52 plexuses) of cases, the bundles are in the posterior part of the middle trunk; in 38.8% (47 plexuses), the bundles are in the posterior part of the middle trunk and the posterior superior part of the inferior trunk. Less frequently, sensory and motor bundles have different localization in the trunks of the brachial plexus: in 7.4% (9 plexuses) of the posterior superior part of the inferior trunk, in 5.8% (7 plexuses) of the

posterior inferior part of the superior and middle trunks, in 5.0% (6 plexuses) of the posterior part of the superior and middle trunks and the posterior part of the inferior trunk.

The ratio of motor and sensory bundles in the brachial plexus trunks is also different: in 55.3% (67 plexuses) of cases, the motor bundle is lower, and the sensory ones are higher; in 38. 0% (46 plexuses), however, the motor bundle is higher, and the sensory bundles are lower; in 5.0% (6 plexuses), the motor bundle is in the middle and the sensory ones are higher and lower; in 1.7% (2 plexuses), the interfascicular localization could not be determined.

In C6, C7, and C8 roots, in 98.3% (119 plexuses) of cases, the motor bundle is localized in the posterior superior part and the sensory bundles are localized in the posterior inferior parts (Figure 3). In rare cases (1.7%-2 plexuses), the thoracodorsal nerve consists of a mixed bundle located in the central medial part.

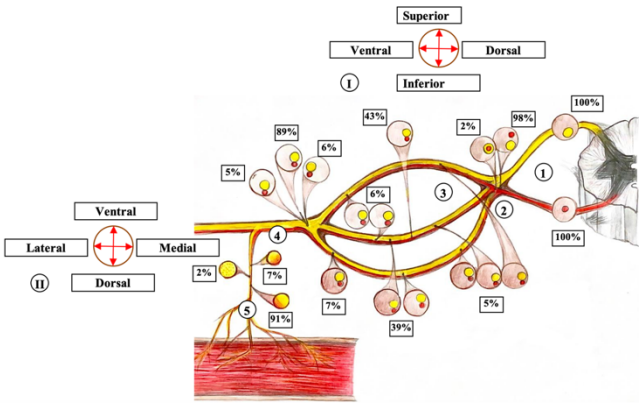

Figure 3. Schematic representation of the variants of the relationship and localization of the sensory (indicated in yellow) and motor (red) bundles of the thoracodorsal nerve along the entire length from the latissimus dorsi muscle to the spinal cord: 1 - in the anterior and posterior roots, 2 - spinal nerve, 3 - upper, the middle and lower trunks of the brachial plexus, 4 - the posterior bundle, 5 - the thoracic nerve. I – coordinate system of fiber localization in roots, spinal nerve, trunks, bundle; II - thoracic nerve.

In the middle third of the anterior root of the spinal cord is the motor bundle, and in the posterior root, the sensory bundles of the thoracodorsal nerve are closely intertwined with other fibers, and it is not possible to determine their localization. The anterior root is formed by two common motor fiber bundles that divide into 7 - 8 spinal cord filaments near the spinal cord. The posterior root is formed by a common bundle of sensory fibers that split into 9 - 10 spinal cord filaments as they approach the spinal cord. With intratubular dissection, it is therefore possible to identify the sensory and motor bundles of the thoracodorsal nerve throughout.

Thus, macro microscopic intratrunk preparation of 121 specimens from 105 cadavers revealed that the thoracodorsal nerve is mixed and consists of 1-3 thin and soft bundles of sensory and one thick and dense bundle of motor nerve fibers. Types of topography of bundles of thoracodorsal nerve along the entire length from latissimus dorsi muscle to spinal cord on the plane: nerve - 3, bundles - 3, trunks - 5, roots of brachial plexus - 2, roots of spinal cord - 1. A method of intra-trunk identification of sensitive and motor bundles has been developed, which is based on determining their number, thickness, density, relationship, and localization.

Discussion

Views on the structure of peripheral nerves have changed three times in the last century[15, 16]. Originally, the concept of fiber tracts and functional nerve topography was developed. The essence of this concept was that the fibers supplying a particular muscle or region are strictly localized in the nerve. The concept is that the fiber bundles are crossed before the nerve is divided into branches, and that these branches are set high in the proximal direction.

Later, a second, opposite view of nerve structure emerged, assuming numerous and irregular anastomoses and division of the bundles along their entire length. However, it was assumed that motor or sensory fibers could be grouped into bundles in a particular quadrant of the nerve. The third, intermediate, view envisages the presence in the distal part of the nerve of sections (up to 21 cm long) with a clearly defined course of nerve fiber bundles, mainly before division into branches.

Therefore, our knowledge of intratruncal topography, especially of the proximal part of the nerve, is still far from certain and accurate[16, 46]. Considering that the above results were obtained in the study of the long nerves of the extremities, we performed a study on the possibilities of intratrunkal topography of the thoracodorsal nerve, which is a short nerve of the brachial

plexus.

We performed intratrunkal preparation on 121 brachial plexus preparations from 105 human cadavers and found that the thoracodorsal nerve is a mixed nerve. This is consistent with the data[29], who found that only 15% of the axons in the thoracodorsal nerve are motor and 85% are sensitive. Our data on the bundle structure (1-4) of the thoracodorsal nerve are consistent with the work where was identified 2-4 bundles of nerve fibers[50].

In our work we managed to isolate the bundles of the thoracodorsal nerve to the roots of the spinal cord and to determine their functional affiliation: the bundles passing through the anterior root are motor; those passing through the posterior root are sensory. The characteristics of the bundles of the thoracodorsal nerve are given sensory - thin and soft, and there are from 1 to 3 of them, at motor bundles there is always only one, this one is thicker and denser in relation to the sensory bundles. The obtained results do not agree with results according to which the enzymatic density in the unmyelinated fibers of sensory bundles is much denser than in the fibers of motor bundles[21]. Apparently, the mechanical and enzymatic density of the bundles differ from each other; in motor bundles, which are dense on contact, the enzymatic activity of the fibers is less pronounced, and in soft, sensitive ones it is higher.

In addition, we identified variants of intraneural topography of bundles to the spinal cord: Nerve - 3, bundles - 3, trunks - 5, roots of brachial plexus - 2, roots of spinal cord – 1 (Figure 3). The most common variant is the course of bundles of thoracodorsal nerve through posterior parts of the nerve itself, the posterior bundle, trunks, roots of brachial plexus and roots of spinal cord. This is in partial agreement with the data where was found that more than 52% of motor fibers are in the posterior part of the thoracic nerve[49].

Based on the data obtained, a method was developed for intratrunkal identification of the sensory and motor bundles of the thoracodorsal nerve based on their number, thickness, density, relationship, and topography. The number of sensory bundles ranges from 1 to 3, and the motor bundle is one in all cases. As for thickness and density, the sensitive bundles are thinner and denser than the motor ones. Depending on the relationship and topography: in the thoracodorsal nerve, the motor bundle is located posteriorly and the sensory ones anteriorly in 98.3% of the cases; in the posterior bundle of the brachial plexus, the fiber bundles are in the posterior inferior part in 89%. In the 2% of the cases, with the sensory bundles always higher up in the nerve when dissecting downward from the front of the recumbent cadaver than the motor bundles. The nerve fiber bundles are also located in the posterior-inferior part of the middle and superior trunks, in the posterior-superior part - of the inferior trunk, with the motor bundle located lower and the sensory bundle higher in 55.3% of the cases and vice versa in 38.0%; in the roots of the brachial plexus, in 98.3% of the cases, the motor bundles are in the posterior superior part and the sensory bundles in the posterior inferior part. In the roots of the brachial plexus, the motor bundle is localized in the posterior superior and the sensory in the posterior inferior in 98.3% of cases; in the middle third of the roots of the spinal cord, the bundles (the sensory in the posterior and the motor in the anterior) are tightly intertwined with other fibers and it is not possible to further determine their localization.

Conclusions

The thoracodorsal nerve is a mixed nerve and consists of sensory and motor bundles with a distinct posterior localization from the latissimus dorsi muscle to the spinal cord. An algorithm for intratrunk identification was developed based on the number, thickness, density, relationship, and topography of the sensory and motor bundles. The data obtained can be used in intraoperative diagnosis of thoracodorsal nerve bundles and in fascicular reconstruction of damaged brachial plexus nerves.

Declaration of Interest

The authors declare that there are no apparent or potential conflicts of interest related to the publication of this article.

References

1. Kwon ST, Chang H, Oh M. Anatomic basis of interfascicular nerve splitting of innervated partial latissimus dorsi muscle flap. J Plast Reconstr Aesthet Surg. 2011; 64(5):e109-14. doi: 10.1016/j.bjps.2010.12.008.

2. Szychta P, Butterworth M, Dixon M, Kulkarni D, Stewart K, Raine C.Breast reconstruction with the denervated latissimus dorsi musculocutaneous flap. Breast. 2013; 22(5):667-72. doi: 10.1016/j.breast.2013.01.001.
3. Park SO, Kim J, Kim IK, Chung JH, Jin US, Chang H. Minimizing donor site morbidity using the interfascicular nerve splitting technique in single-stage latissimus neuromuscular transfer for facial reanimation. J Plast Reconstr Aesthet Surg. 2021;74(5):1101-1160. doi: 10.1016/j.bjps.2020.10.030.
4. Semyonov D.Yu., Vasil'ev Yu.L., Dydykin S.S., Stranadko E.F., Shubin V.K., Bogomazov Yu.K., Morokhotov V.A., Shcherbyuk A.N., Morozov S.V., Zakharov Yu.I. Antimicrobial and antimycotic photodynamic therapy (review of literature). Biomedical Photonics. 2021;10(1):25–31. https://doi.org/10.24931/2413-9432-2021-10-1-25-31
5. Samardzic MM, Grujicic DM, Rasulic LG, Milicic BR. The use of thoracodorsal nerve transfer in restoration of irreparable C5 and C6 spinal nerve lesions. Br J Plast Surg. 2005;58(4):541-6. doi: 10.1016/j.bjps.2003.12.027.
6. Beris A, Gkiatas I, Gelalis I, Papadopoulos D, Kostas-Agnantis I. Current concepts in peripheral nerve surgery. Eur J Orthop Surg Traumatol. 2019;29(2):263-269. doi: 10.1007/s00590-018-2344-2.
7. Gordon T. Peripheral nerve regeneration and muscle reinnervation. Int J Mol Sci. 2020;21(22):8652. doi: 10.3390/ijms21228652.
8. Gruber H. Identification of motor and sensory funiculi in cut nerves and their selective reunion. Br J Plast Surg. 1976;29(1):70-3. doi: 10.1016/0007-1226(76)90096-5.
9. Bonnel F. Microscopic anatomy of the adult human brachial plexus: an anatomical and histological basis for microsurgery. Microsurgery. 1984;5(3):107-18. doi: 10.1002/micr.1920050302.
10. Solanki C, Socolovsky M, Devi BI, Bhat DI. Nerve repair: Bridging the gap from "limp" to "limb". Neurol India. 2019;67(Supplement):S16-S19. doi: 10.4103/0028-3886.250712.
11. Jabaley ME, Wallace WH, Heckler FR. Internal topography of major nerves of the forearm and hand: a current view. J Hand Surg Am. 1980;5(1):1-18. doi: 10.1016/s0363-5023(80)80035-9.
12. Boyd KU, Nimigan AS, Mackinnon SE. Nerve reconstruction in the hand and upper extremity. Clin Plast Surg. 2011;38(4):643-60. doi: 10.1016/j.cps.2011.07.008.
13. Agarwal P., Bajaj J., Sharma D. Techniques for Differentiating Motor and Sensory Fascicles of a Peripheral Nerve-A Review. Indian Journal of Neurotrauma 2020; 17(01): 28-32. DOI: 10.1055/s-0040-1713458.
14. McKinley J.C. The intraneural plexus of fasciculi and fibres in the sciatic nerve. Archives of Neurology and Psychiatry. Chicag, 1921; Vol. 6. P. 377-399.
15. Sunderland S. The intraneural topography of the radial, median and ulnarnerves. Brain, 1945; Vol. 68 (4). P. 243–298. https://doi.org/10.1093/brain/68.4.243.
16. Sunderland S. The pros and cons of funicular nerve repair. J. Hand. Surg. 1979; 4: 201-211. https://doi.org/10.1016/S0363-5023(79)80155-0.
17. Frey M. Avulsion injuries to the brachial plexus and the value of motor reinnervation by ipsilateral nerve transfer. J Hand Surg. Br. 2000; 25: 323-324.
18. Jabaley M.E. Current concepts of nerve repair. Clin Plast Surg. 1981;8(1):33–44. https://doi.org/10.1016/S0094-1298(20)30471-5.
19. Williams H.B., Jabaley M.E. The importance of internal anatomy of the peripheral nerves to nerve repair in the forearm and hand. Hand Clin. 1986;2(4): 689–707. https://pubmed.ncbi.nlm.nih.gov/3793767/.
20. Zhong S.Z., Wang G.Y., He Y.S., Sun B.. The relationship between structural features of peripheral nerves and suture methods for nerve repair. Microsurgery. 1988; 9: 181-187. DOI: 10.1002/micr.1920090304.
21. Deutinger M., Girsch W., Burggasser G., Windisch A., Joshi D., Mayr N., Freilinger G. Peripheral nerve repair in the hand with and without motor sensory differentiation. J. Hand. Surg. Am. 1993:18 (3): 426–432. https://doi.org/10.1016/0363-5023(93)90085-H.
22. Mafi P., Hindocha S., Dhital M., Saleh M.. Advances of peripheral nerve repair techniques to improve hand function: a systematic review of literature. Open Orthop. J. 2012:6:60-68. doi: 10.2174/1874325001206010060.
23. Xianyu M., Zhenggang B., Laijin L. Identification of the sensory and motor fascicles in the peripheral nerve: A historical review and recent progress. Neurol. India.2016;64 (5): 880-885. DOI: 10.4103/0028-3886.190241.
24. Engel J., Ganel A., Melamed R., Rimon S., Farine I. Choline acetyltransferase for differentiation between human motor and sensory nerve fibers. Ann. Plast. Surg. 1980;4 (5): 376-380. DOI: 10.1097/00000637-198005000-00004.
25. Petrova E.S., Pavlova N.V., Korzhevsky D.E. advanced morphological approaches to the study of peripheral nerve regeneration. Modern academic journal. 2012; 2(3):15-29 doi: 0.17816/MAJ12315-29
26. He Y.S., Zhong S.Z. Acetylcholinesterase: a histochemical identification of motor and sensory fascicles in human peripheral nerve and its use during operation. Plast. Reconstr. Surg. 1988;82 (1):125-132.
27. Kawasaki Y., Yoshimura K., Harii K., Park S. Identification of myelinated motor and sensory axons regenerating mixed nerve. J. Hand Surg. Am. 2020;25(1):104-111. Doi: 10.1053/jhsu.2000.jhsu025a0104.
28. Gesslbauer B., Hruby L.A., Roche A.D., Farina D., Blumer R., Oskar C. Aszmann O.C. Axonal components of nerves innervating the human arm. Ann. Neurol. 2017; 82 (3): 396-408. https://doi.org/10.1002/ana.25018.
29. Ganel A., Farine I., Aharonson Z., Horoszowski H., Melamed R., Rimon S. Intraoperative nerve fascicle identification using choline acetyltransferase: a preliminary report. Clin. Orthop. Relat. Res. 1982; 165: 228-32.
30. Kanaya F.. Mixed nerve suture facilitated by enzyme-staining techniques. Tech. Hand Up. Extrem. Surg. 2000;6(3):140-144.
31. Cui B, Wu C, Chen L, Ramirez A, Bearer EL, Li WP, Mobley WC, Chu S. One at a time, live tracking of NGF axonal transport using quantum dots. Proc Natl Acad Sci U S A . 2007; 21;104(34):13666-71. doi: 10.1073/pnas.0706192104.
32. Meng X., Lu L., Wang H., Liu B. Differentiation between the motor and sensory fascicles of the peripheral nerves from adult rats using annexin V-CdTe-conjugated polymer. Neurol India. 2011;59 (3):333–338. DOI: 10.4103/0028-3886.82710.
33. Turkof E., Jurasch N., Knolle E., Schwendenwein I., Habib D., Unger E., Reichel M., Losert U. Motor evoked potentials enable differentiation between motor and sensory branches of peripheral nerves in animal experiments. J. Reconstr. Microsurg. 2006; 22:525-532. DOI: 10.1055/s-2006-951318.
34. Baitinger V.F., Silkina K.A., Baitinger A.V., Fedorov Ye.V. Total breast reconstruction: from rejection to the gold standard. Issues of Reconstructive and Plastic Surgery. 2014;3:5-19. (In Russ).
35. Palmieri R.M., Ingersoll C.D., Hoffman M.A.. The Hoffmann reflex: methodologic considerations and applications for use in sports medicine and athletic training research. J. Athl. Train. 2004;39 (3):268–277.
36. Litvinenko I. V., Odinak M. M., Zhivolupov S. A., Bulatov A. R., Rashidov N. A., Bardakov S. N. Clinical and instrumental characteristics of traumatic lesions of peripheral nerves of limbs. Vestnik of Russian military medical Academy. 2018;3(63):50-56.
37. Vasil'ev YuL, Rabinovich SA, Dydykin SS, Bogoyavlenskaya TA, Kashtanov AD, Kuznetsov AI. Evaluation of dentists regulatory systems stress during the provision of dental care according to pulse oximetry data. Stomatologiya. 2020;99(6):89-93. (In Russ.) https://doi.org/10.17116/stomat20209906189
38. Rabinovich SA, Razumova SN, Vasil'ev YL. Functional cardiovascular assessment in dentists performing local anesthesia in out-patient settings. Stomatologiia (Mosk). 2017;96(1):20-22. doi: 10.17116/stomat201796120-22.
39. Xie S, Xiang B, Bu S, Cao X, Ye Y, Lu J, Deng H. Rapid identification of anterior and posterior root of cauda equina nerves by near-infrared diffuse reflectance spectroscopy. J Biomed Opt. 2009;14(2):024005. doi: 10.1117/1.3086611.

40. Skorpil M., Karlsson M., Nordell A. Peripheral nerve diffusion tensor imaging. Magn Reson Imaging. 2004;22:743-745. https://doi.org/10.1016/j.mri.2004.01.073.
41. Chhabra A., Thakkar R.S., Andreisek G., Chalian M., Belzberg A.J., Blakeley J., Hoke A., Thawait G.K., Eng J., Carrino J.A. Anatomic MR imaging and functional diffusion tensor imaging ofperipheral nerve tumors and tumorlike conditions. AJNR Am. J. Neuroradiol. 2013;34:802-807. DOI: https://doi.org/10.3174/ajnr.A3316
42. Heckel A., Weiler M., Xia A., Ruetters M., Pham M., Bendszus M., Heiland S., Baeume P. Peripheral Nerve Diffusion Tensor Imaging: Assessment of Axon and Myelin Sheath Integrity. 2015;26;10(6):e0130833. doi: 10.1371/journal.pone.0130833
43. Gasparotti R., Shah L. Brachial and Lumbosacral Plexus and Peripheral Nerves. - Diseases of the Brain, Head and Neck, Spine. 2020:241-254.
44. Pellerin M., Kimball Z., Tubbs R.S., Nguyen S., Matusz P., Cohen-Gadol A.A., Loukas M.. The prefixed and postfixed brachial plexus: a review with surgical implications. Surg. Radiol. Anat. 2010;32:251–260. DOI https://doi.org/10.1007/s00276-009-0619-3.
45. Stewart J.D. Peripheral nerve fascicles: anatomy and clinical relevance. Muscle Nerve. 2003;28 (5):525-541. doi: 10.1002/mus.10454.
46. Isla A., Pozuelos I.J. Anatomic study in cadaver of the motor branch of the musculocutaneous nerve. Acta Neurochir Suppl. 2011;108:227-232.
47. Samardzic M.M., Grujicic D.M., Rasulic L.G., Milicic B.R. The use of thoracodorsal nerve transfer in restoration of irreparable C5 and C6 spinal nerve lesions. Br. J. Plast. Surg. 2005;58(4): 541-546. DOI:https://doi.org/10.1016/j.bjps.2003.12.027.
48. Lu W., Xu J.G., Wang D.P., Gu Y.D. Microanatomical study on the functional origin and direction of the thoracodorsal nerve from the trunks of brachial plexus. Wiley InterScience. 2008;21(6):509-513. htts://doi.org/10.1002/ca.20656.
49. Raksakulkiat R., Leechavengvongs S., Malungpaishrope K., Uerpairojkit C., Witoonchart K., Chongthammakun S. Restoration of winged scapula in upper arm type brachial plexus injury: anatomic feasibility. J. Med. Assoc. Thai. 2009;92(6):S244-250.
50. Mason J.M., O'Leary T.J. Effects of Formaldehyde Fixation on Protein Secondary Structure: A Calorimetric and Infrared Spectroscopic Investigation. The Journal of Histochemistry and Cytochemistry. 1991;39(2): 225-229. https://doi.org/10.1177/39.2.1987266.
51. Zhandarov K.A, Ogarev E.V, Chekanov M.S, Vasil'ev Yu.L, Meylanova R.D, Kryuchko P.V, Dydykin S.S. Combined method of treatment of dentists in the early stages of osteochondrosis of the cervical spine. J Int Dent Med Res 2021; 14(2): 825-834.