Topography of the Human Ulnar Nerve for Mounting a Neuro-Prosthesis with Sensory Feedback

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This article presents the performed experimental measurements for connecting a sensory feedback neuro-prosthesis to the peripheral nervous system of a patient with forearm amputation. The experiments focused on the ring finger motion's neuron control in the forearm prosthesis and on the neural path transmission of the tactile sensation coming from the pressure sensors fitted on the small finger phalanges (F5). For the ring finger, both motor control and sensory feedback are transmitted through the ulnar nerve's motor axons, respectively by the ulnar nerve's sensory axons. At the beginning of this study, the topography of the ulnar nerve has been performed, in order to identify the axons by which motor controls are transmitted for the small finger movement (F5) and the axons through which small finger (F5) tactile information is transmitted. A Carl Zeiss S8 electronic microscope was used to analyze the ulnar nerve's transverse sections for an anonymous patient. Cross sections in the ulnar nerve have been examined, from the tip of the small finger (F5) to the shoulder area. The separately mappings of motor and sensory axons from the ulnar nerve at the wrist's level and at the elbow's level were then performed. 3D modeling was performed using CATIA software solution for mapping the axon topography in the ulnar nerve. By means of the ulnar nerve's 3D topographic map, the optimal place for the implantation of both motor control electrodes and small finger (F5) sensory feedback electrodes were identified in the particular case of a patient with forearm amputation. Subsequently, by surgical procedures, experimental implantation of a motor control electrode for the small finger (F5) from a neuro-prosthesis was performed as well as a sensory feedback electrode for the same finger. For the next two weeks, measurements were made while the patient has been learning to move the small finger (F5) of the neuro-prosthesis and feel the tactile sensation from this finger. After these two weeks the electrodes were extracted from the patient's stump by surgery.

Keywords: ulnar nerve, topography*, neuron control, neuro-prosthesis, forearm amputation, sensory feedback electrodes, control electrodes, CATIA 3D modeling*

In order to provide a patient having an arm lost by amputation with healthy hand-like performances, similar to the ones in the limb lost by amputation, a neuro-prosthesis must operate in real-time with biosignals from the motor nerve fibers at the stump level, and it must transmit biosignals from the prosthesis tactile sensors to the sensitive nerve fibers in the stump also in real-time. The connection of a neuro-prosthesis to the patient's peripheral nervous system is performed by surgery: the motor elements of the neuro-prosthesis fingers connect to the motor axons from the patient's stump and the sensory interface of the neuro-prosthesis connects to the sensory axons from the patient's stump.

The movements that a healthy hand accomplishes result from the contractions of 27 muscles in the forearm, palm and fingers; these muscles are controlled by three nerves (median, ulnar and radial). Each of the three nerves contains hundreds of axons grouped in motor and sensitive bundles. Axons from the motor fibers are used to control hand and fingers movements, and axons from the sensitive fibers are used for transmitting sensory feedback from the sensitive receptors in the fingers, palm, forearm and arm (tactile sensations, temperature and humidity sensations, etc.). Sensory feedback is of great importance in achieving a wide range of complex moves with hands help. Without sensory feedback, fingers and hands movements would be inaccurate. Feedback transmitted through the sensory fibers of the three nerves (from the sensory receptors in the fingers, palm, arm and forearm) make motion motor controls (transmitted through the motor nerve fibers of the three nerves) able to be adjusted / modeled in real-time so as to obtain the patient's desired precision for each movement. In order for the patient to be able to achieve a complex and precise movement with the neuro-prosthesis, it must be connected to both the motor and the sensory axons in the three nerves (median, ulnar and radial) at the stump level.

Connecting the neuro-prosthesis to the peripheral nervous system at the stump level requires topography knowledge of all nerve fibers, of the axons and the dendrites of the three nerves. Over the last few years, the topography of these three nerves has become a topic of significant interest, due to the technological development in making neuro-prosthesis for the amputated upper limbs.

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The median nerve fibers' topography was first presented in detail in [1]. As for the ulnar nerve, a detailed presentation of its topography was not found in the specialized literature. In the first stage of this study, the authors of this article have themselves achieved the mapping of all the nerve fibers, axons, and dendrites in the ulnar nerve.

A particular priority was the identification of axons and dendrites in the ulnar nerve that transmit the tactile sensation from the tip of the small finger F5, as they were going to be used to connect with the neuro-prosthesis sensory interface in the case of a patient with a forearm amputation.

State of the art for the techniques of surgical implantation of electrodes

Despite technological advances in recent years, there are no standard surgical procedures for fitting a neuro-prosthesis on an amputation stump [2]. Connecting a neuro-prosthesis to the peripheral neural system in the patient's stump is solely performed by surgery, which makes the surgeon's role essential. In the specialized literature, increasingly numerous experimental clinical trials have been reported, focusing on patients with amputated upper limbs who managed to command a neuro-prsthesis with neuron signals from the amputation stump [3].

Numerous technological bottlenecks still exist in the field of neuro-prosthesis, mainly in what concerns the selective acquisition of as many neural motor control signals as possible for the various types of neuro-prosthesis movements (fingers, palm and forearm) [4]. The geometry of the median, ulnar and radial nerves makes it difficult to obtain a clear and accurate acquisition of signals which circulate through the axons [5]. If the neuro-prosthesis is going to replace the arm lost by amputation, it must be connected bi-directionally: both with the motor and the sensory axons at the level of the three nerves in the amputation stump.

The electrodes implantation method in the amputation stump, in order to acquire distinct and accurate motor and sensory neural control signals, constitutes still a problem with no complete solutions [6]. Certain electrodes are implanted longitudinally, others transversally and others in a circular manner around the median / ulnar / radial nerve. In the specialized literature, several categories of electrodes for the acquisition of neural signals are mentioned: REMI (regenerative multielectrode interface), MCRE (micro channel roll electrode), LIFE (longitudinally implanted intrafascicular electrodes), TIME (transverse intrafascicular electrodes), CWIE (coiled wire intrafascicular electrodes), FINE (flat-interface nerve electrode), etc. During surgery, the electrodes are anchored by the median/ulnar motor nerve so as to acquire the neural electrical signals as accurately as possible. The amputation stump muscle mass' complex dynamics, however, makes electrodes cause injuries to the nerve or to the nearby blood vessels in some situations (especially for longitudinal electrodes) [7]. Implantation of as many electrodes as possible in the amputation stump could solve a part of this problem. Electrode implantation should be done in such a way as to enable selective acquisition of signals from among hundreds of motor and sensory neural signals from each of the three nerves (median, ulnar and radial). All these signals are electrically similar (amplitude of 60-90 mV and duration of 2ms). In the case of healthy hand motions, through the hundreds of axons in each of the three nerves, thousands of neural impulses (60-90 mV, 2ms) from the nerve ganglia to the muscle fibers, and further thousands of neural impulses (60-90 mV, 2ms) from sensory receptors in the fingers and palm to the nerve ganglia are transmitted.

As we approach the amputation area of a stump, the number of neural signals in the three nerves decreases, because, by amputation, the parts to be controlled and the ones to convey numerous sensory signals have been lost. At the end of an amputation stump, only motor signals will be detected, since most of the sensory receptors were eliminated by amputation (palm and fingers). This situation requires that the electrodes for transmitting sensory signals (from the neuro-prosthesis to the patient) should be implanted at the end of the sensory axons and dendrites at the amputation site. With regard to the placement of the motor signal acquisition electrodes, they should be placed on the motor axons corresponding to the stump muscles that were involved (before amputation) in the palm and fingers movement.

The implantation of acquisition and stimulation electrodes is performed by the surgeon who needs to thoroughly know the complete topography of nerve fibers, axons and dendrites within the three nerves. The detailed topography of all nerve fibers and axons (both motor and sensory) in the median nerve has been recently achieved [1]. For the ulnar nerve no such topography has been reported in the literature so far, but it has been done in this study.

Experimental part

Mapping method for motor and sensitive nerve fibers in the ulnar nerve

For mapping the topography of the ulnar nerve, 2 left arms from two body donors were investigated in the anatomy laboratory of Carol Davila University of Medicine and Pharmacy, the Faculty of Medicine. The protocol was approved by the Ethics Committee of the Bucharest Emergency University Hospital. The dissections were made layer by layer through transversal incisions along the forearm the volar face from the elbow to the distal phalanges of fingers 4 and 5 and the dorsal face of the hand. In order not to damage the tissues of each forearm, they were treated with formalin. In the dissections a size 11 and 15 scalpel were used.

During dissections each ulnar nerve muscle and branch was noted. Within each section performed in the ulnar nerve, all components and all motor and sensory axons were labeled under the microscope. Special attention has been paid to identifying the sensory dendrites that transmit the tactile sensations from the small finger F5. For better use, these dendrites were named OpCh5.

Figure 1 shows one of the two arms used for dissection. It illustrates the topography of the nerve fibers in the ulnar nerve.

3D modeling of the sensory axons in the ulnar nerve

For the 3D modeling of the inner structure of the ulnar nerve, the CATIA software package was used. The CATIA software modules even enable ergonomic studies, project management, electronic systems design, biological systems modeling, and so on. CATIA also has an interface easy to work with and customizable menus. Of these, the following modules were used to model the internal structure of the ulnar nerve:

1. The Sketcher module enables drawing a sketch of a 2D profile (flat plane).
2. The Part Design Module, enabling the design of 3D parts (in space).
3. The Drafting module, possessing the tools needed to create 2D and 3D industrial drawings, the quotation being done automatically / manually.

Microscope images of the ulnar nerve cross sections were used for the 3D modeling of the ulnar nerve by means of the CATIA software package. A performance calculator [8] was used. The figure below illustrates the global 3D structure of the ulnar nerve with all motor and sensory branches.

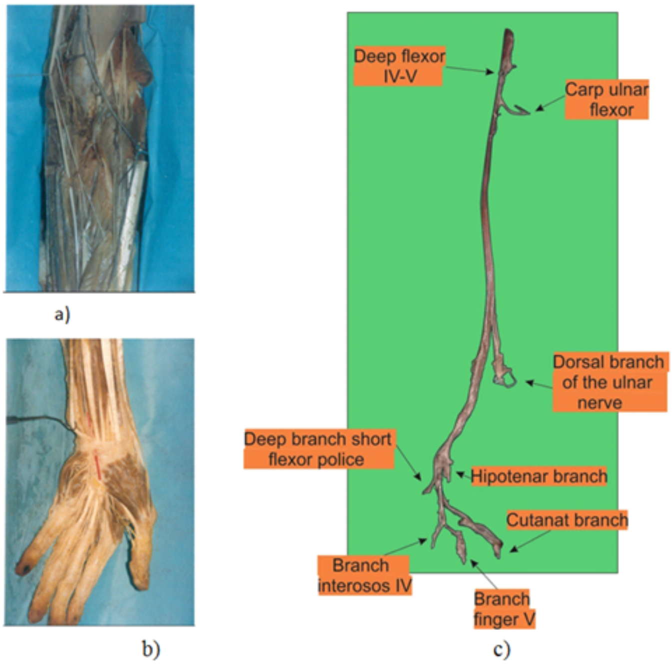

Fig. 1. Identification of ulnar nerve in forearm a) and palm b) c) Topography of the ulnar nerve in the forearm and palm

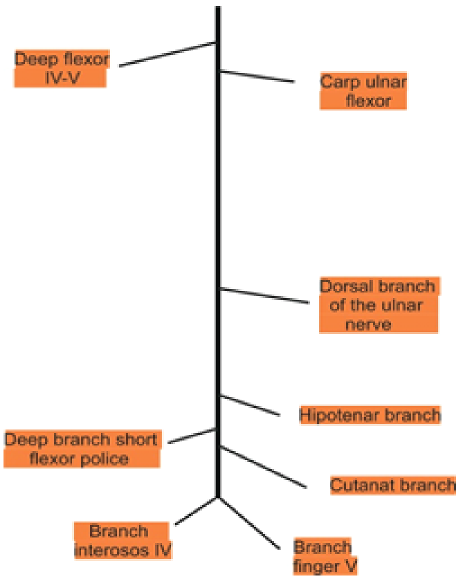

Fig. 2. The 3D modeling of ulnar nerve topography

The 3D ulnar nerve modeling has proved to be very useful for implementing the sensory feedback function in forearm neuro-prosthesis. In this modeling, information from the scientific articles has been taken into account [1, 9]. By the 3D model, in the particular case of a patient with forearm amputation, the optimal position for implanting a control electrode for the ring finger of a neuro-prosthesis in the amputation stump was identified, as well as the optimal implantation position for a sensory feedback electrode for the same finger of the neuro-prosthesis.

Results and discussions

Surgical implementation of two electrodes for the motor control and sensory feedback of the little finger F5 of a neuro-prosthesis

This study was conducted in accordance with the Helsinki Declaration of 1975 at the Bucharest Emergency University Hospital. The authors declare that all experiments on human subjects were conducted in accordance with the Declaration of Helsinki http://www.wma.net and that all procedures were carried out with the adequate understanding and written consent of the subjects. The Ethics Commission of the Bucharest Emergency University Hospital approved the working protocol for the implantation of two electrodes in the patient's stump. In this study, type BIONEN longitudinal electrodes were implanted at the level of the stump. Anchoring was done with 3 loops of muscle fibres. Two motor control electrodes were implanted in the motor branch of the ulnar nerve for the small finger (F5). Two sensory feedback electrodes were implanted in the sensory branch of the ulnar nerve in charge of transmitting the tactile sensation from the little finger (F5).

The two pairs of electrodes were implanted in different places in order to reduce the interference between the biosignals of neural motor control and sensory feedback. Two incisions with a length of 3 mm each were made.

The patient was given antibiotic treatment before surgery (Augmentin 1 g/12 h for one day and after surgery (Augmentin 1g/12h for 4 day). Two days later the implants were removed by surgery with general anesthesia. The patient had no post-surgery or post-medication pain. The patient had no fever, and no signs of local infection were identified. The surgery did not cause complications or side effects. During the interval in which the patient had the implants, s/he reported significant reduction of phantom limb pain. During surgery, it was found that the motor nerve fibers of the little finger were healthy.

Patients training for neuro-prosthesis control and for the use of the sensory feedback given by the prosthesis

During the brief time interval in which the patient had the implanted electrodes, s/he had special training so as to succeed in controlling the little finger F5 of the neuro-prosthesis with the neural signals acquired from the ulnar nerve.

Fig. 3. Patient training for F5 finger control from a neuroprostesis [10]

A neuro-prosthesis with sensory feedback was used in the training, as shown in the picture below. The picture also shows the software interface that monitors the tactile pressure on the little finger F5 of the neuro-prosthesis. Patient training has consisted in simultaneous movements with the little finger F5 from the healthy arm and the little finger F5 of the neuro-prosthesis. The structure of the exercises has been taken from other training programs made by other people with amputations that have been reported in other scientific articles [11, 12]. In some articles, amputees perform a special training connected to virtual environments to gain the confidence they need to manage prosthesis [13, 14]. During training, the necessary adjustments (for the neuro-prosthesis) have been made on the signal processing levels, so that the patient managed to control the movement of the little finger F5 of the neuro-prosthesis after the first training day. The sensory feedback signal was also tuned so as to provide the patient with a proper tactile sensation from the little finger F5 of the neuro-prosthesis, similar to the little finger F5 sensation from the healthy hand.

Fig. 4. Monitoring the tactile feedback signal from the fingers of neuro-prosthesis

Conclusions

This study performed measurements have led to mapping the topography of the internal structure of the human ulnar nerve (for motor control axons and the sensory axons and dendrites). Within these measurements, the complete pathway throughout the human ulnar nerve of the sensory dendrite in charge with transmitting the tactile sensation from the little finger (F5) within the peripheral neural system has been identified. This dendrite was called OpCerg 5. This name was registered in the international database Deusches Register Klinischer Studien (DRKS00015331).

The human ulnar nerve topography was then 3D modeled using the CATIA software package. The ulnar nerve 3D modeling has been used in identifying the optimal site for motor and sensory electrodes implantation in the patient's stump, for controlling the little finger F5 of a neuro-prosthesis. Two pairs of electrodes were then surgically implanted into the patient's amputation stump and the neuro-prosthesis was connected to the patient's peripheral nervous system in the stump. The neuro-prosthesis was connected to the motor and sensory axons of the patient's amputation stump. In the two-day training session, the patient has managed to control the little finger F5 of the neuro-prosthesis with neural signals. The patient also managed to feel tactile sensations from the little finger F5 of the neuro-prosthesis similar to the tactile sensations from the healthy hand. The results obtained in this study recommend further research so as the patient may control all the fingers of the neuro-prosthesis.

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