SUMMARY
PhD THESIS

NEURO-ELECTROPHYSIOLOGICAL CORRELATIONS IN THE FOLLOW UP OF THE UPPER LIMB’S FUNCTIONAL REHABILITATION IN BRACHIAL PLEXUS PALSIES

SCIENTIFIC COORDINATOR
PROF. DR. STAMATE Teodor

PhD STUDENT
TROFIN Dan

2023
CONTENTS .................................................................................................................. 1
ABBREVIATIONS ........................................................................................................ III
INTRODUCTION ........................................................................................................... 1
GENERAL PART ............................................................................................................ 3
CHAPTER ONE ........................................................................................................... 3
I.1 Anatomy of the brachial plexus ........................................................................... 3
I.2 Etiology of brachial plexus lesions .................................................................... 5
I.3 Physiopathology of peripheral nerve lesions ...................................................... 6
CHAPTER TWO ........................................................................................................... 9
II.1 Clinical aspects of brachial plexus lesions ......................................................... 9
II.1.1 Upper brachial plexus paralysis (C5-C6) ....................................................... 9
II.1.2 Middle brachial plexus paralysis (C7) .......................................................... 10
II.1.3 Inferior brachial plexus paralysis (C6-T1) .................................................... 10
II.1.4 Total brachial plexus paralysis ................................................................. 10
II.2 Clinical aspects of terminal nerve lesions ....................................................... 11
II.2.1 Axillary nerve paralysis ............................................................................ 11
II.2.2 Musculocutaneous nerve paralysis ............................................................ 11
II.2.3 Radial nerve paralysis ............................................................................. 11
II.2.4 Median nerve paralysis ............................................................................ 13
II.2.5 Ulnar nerve paralysis ............................................................................. 15
CHAPTER THREE ..................................................................................................... 17
III.1 Classification of brachial plexus lesions from surgical perspective .............. 17
III.2 Surgical strategies in brachial plexus palsies .................................................. 18
III.2.1 Neurolisis .............................................................................................. 18
III.2.2 Neuroraphy .......................................................................................... 18
III.2.3 Nerve graphing ...................................................................................... 19
III.2.4 Neurtization ........................................................................................... 19
III.2.5 Tendon transfers ................................................................................... 22
III.2.6 Muscle transfers ..................................................................................... 22
III.2.7 Associated techniques .......................................................................... 23
CHAPTER FOUR ....................................................................................................... 24
IV.1 Electroneuromyography in assessing brachial plexus lesions ...................... 24
IV.1.1 Nerve conduction in brachial plexus lesions .............................................. 24
IV.1.1.a Importance of saltatory conduction in peripheral nerves ..................... 24
IV.1.1.b Motor conduction studies ................................................................... 24
IV.1.1.c Sensory conduction studies .................................................................. 26
IV.1.1.d Influence of temperature in nerve conduction studies….. 27
IV.1.1.e Late response studies…………………………………… 27
IV.1.1.f Particular anatomic anastomosis……………………… 28
IV.2 Electromyography in brachial plexus injuries…………….. 29
IV.2.1 Spontaneous pathological activity …………………….. 29
IV.2.2 Motor unit action potential analysis…………………… 30
IV.2.3 Electromyographic differential diagnosis……………… 32
IV.3 Somatosensory evoked potentials………………………… 32
IV.4 Transcranial magnetic stimulation………………………… 33
IV.5 Imaging techniques of muscles and nerves………………….. 37
IV.5.1 CT scan………………………………………………………….. 38
IV.5.2 MRI technique………………………………………………… 38
IV.5.3 Ultrasonography……………………………………………… 38
CHAPTER FIVE
Notions of brachial plexus palsies rehabilitation………………… 39
PERSONAL PART…………………………………………………….. 41
INTRODUCTION………………………………………………………… 41
MOTIVATION OF THE THESIS…………………………………… 42
MAIN OBJECTIVES…………………………………………………… 42
CHAPTER SIX: Neuro-electrophysiological follow up study of brachial plexus palsies……………………………………… 43
 VI.1 Introduction…………………………………………………………. 43
 VI.2 Demographic data………………………………………………… 44
 VI.3 Material and methods …………………………………………. 50
 VI.4 Results……………………………………………………………… 58
 VI.5 Discussions………………………………………………………… 71
 VI.6 Conclusions………………………………………………………… 76
CHAPTER SEVEN: Case study: Psychomotricity – neuroplasticity in brachial plexus lesions………………………………… 77
 VII.1 Introduction………………………………………………………… 77
 VII.2 Selected cases of brachial plexus palsies…………………. 79
 VII.3 Material and methods………………………………………… 84
 VII.4 Results……………………………………………………………… 85
 VII.5 Discussions………………………………………………………… 91
 VII.6 Conclusions………………………………………………………… 95
CHAPTER EIGHT: DISCUSSIONS………………………………………. 96
GENERAL CONCLUSIONS…………………………………………… 116
The thesis contains:

- **131 pages** (General part: 40 pages, Personal part: 80 pages);
- 74 figures;
- 28 tables;
- 153 bibliographic references.

This summary presents a selective iconography and selective bibliographic references from the thesis, respecting the indenting of figures and tables, the list of abbreviations, as well as the thesis summary in extenso.

**Keywords:** brachial plexus, transcranial magnetic stimulation, brain mapping, electroneuromyography.
<table>
<thead>
<tr>
<th>No.</th>
<th>Abbreviation</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AP</td>
<td>Action potential</td>
</tr>
<tr>
<td>2</td>
<td>APB</td>
<td>Abductor pollicis brevis</td>
</tr>
<tr>
<td>3</td>
<td>BB</td>
<td>Biceps brachii</td>
</tr>
<tr>
<td>4</td>
<td>BP</td>
<td>Brachial plexus</td>
</tr>
<tr>
<td>5</td>
<td>CMAP</td>
<td>Compound Muscle Action Potential</td>
</tr>
<tr>
<td>6</td>
<td>CMCT</td>
<td>Central Motor Conduction Time</td>
</tr>
<tr>
<td>7</td>
<td>CNS</td>
<td>Central nervous system</td>
</tr>
<tr>
<td>8</td>
<td>EDX</td>
<td>Electrodagnosis</td>
</tr>
<tr>
<td>9</td>
<td>EMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>10</td>
<td>ENMG</td>
<td>Electroneuromyography</td>
</tr>
<tr>
<td>11</td>
<td>Fib</td>
<td>Fibrillation potentials</td>
</tr>
<tr>
<td>12</td>
<td>FD</td>
<td>Flexor digitorum</td>
</tr>
<tr>
<td>13</td>
<td>FDI</td>
<td>First dorsal interosseous muscle</td>
</tr>
<tr>
<td>14</td>
<td>fMRI</td>
<td>Functional magnetic resonance imaging</td>
</tr>
<tr>
<td>15</td>
<td>m. muscle</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>MEP</td>
<td>Motor evoked potential</td>
</tr>
<tr>
<td>17</td>
<td>MRC</td>
<td>(British) Medical Research Council</td>
</tr>
<tr>
<td>18</td>
<td>MRI</td>
<td>Magnetic resonance imaging</td>
</tr>
<tr>
<td>19</td>
<td>MU</td>
<td>Motor unit</td>
</tr>
<tr>
<td>20</td>
<td>MUAP</td>
<td>Motor unit action potential</td>
</tr>
<tr>
<td>21</td>
<td>n. nerve</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>NEMS</td>
<td>Neuromuscular electric stimulation</td>
</tr>
<tr>
<td>23</td>
<td>NMJ</td>
<td>Neuromuscular junction</td>
</tr>
<tr>
<td>24</td>
<td>OTR</td>
<td>Osteotendinous reflexes</td>
</tr>
<tr>
<td>25</td>
<td>PNF</td>
<td>Neuromuscular proprioceptive facilitation</td>
</tr>
<tr>
<td>26</td>
<td>PNS</td>
<td>Peripheral nervous system</td>
</tr>
<tr>
<td>27</td>
<td>PSW</td>
<td>Positive sharp waves</td>
</tr>
<tr>
<td>28</td>
<td>SNAP</td>
<td>Sensory Nerve Action Potential</td>
</tr>
<tr>
<td>29</td>
<td>SSEP</td>
<td>Somatosensory evoked potentials</td>
</tr>
<tr>
<td>30</td>
<td>TENS</td>
<td>Transcutaneous electric nerve stimulation</td>
</tr>
<tr>
<td>31</td>
<td>TL</td>
<td>Terminal-Lateral</td>
</tr>
<tr>
<td>32</td>
<td>TMS</td>
<td>Transcranial Magnetic Stimulation/</td>
</tr>
<tr>
<td>33</td>
<td>TT</td>
<td>Terminal-terminal</td>
</tr>
</tbody>
</table>
Motivation and objectives of the research

The perspective of ongoing electric signals within the motor cortex, conditioned by long term rehabilitation strategies (doubled by adherence to the treatment protocol), is of interest related to understanding how cerebral plasticity is being modulated in adult traumatic brachial plexus lesions.

Proving the need of long-term rehabilitation, even contrary to the sometimes less visible results, can be the trigger point for future research and therapy strategies. The aim of the study is to help patients with brachial plexus (BP) palsies, by providing information useful to orientate the therapeutic approach, motivated by the perspective of a better quality of life.

The main objectives of the research consist in proving evidence of the following:
- a long term rehabilitation protocol is favorable for the patient; it can correlate with rehabilitation of the upper limb’s functionality;
- even in case of a poor or absent recovery, rehabilitation therapy facilitates active cortical plasticity in representation of the affected limb.

The secondary objectives aim towards finding correlations between the found results, demonstrating the following:
- the electrodiagnosis results (obtained at the ENMG and/or TMS) correlate themselves;
- the electrodiagnosis results correlate with dynamometric parameters (muscle strength) and amelioration of the motor deficit.

Introduction

Adult BP palsies are an important cause of disability, causing a profound impact upon people in nowadays dynamic society. Rehabilitation of this pathology is very often difficult. The negative impact is not only upon the professional situation, but also upon the psychological and social life of the patients.

The actual context is fulfilled by a continuous increase in the number of traffic accidents, as well as the increasing attractivity into practicing risky, dangerous sports.

The first part of the thesis is a review of actual notions of anatomy and nervous pathophysiology, as well as the various microsurgical reconstructive options available, and also the electrodiagnosis methods: electroneuromyography and transcranial magnetic stimulation.

The special part of the thesis consists of a retrospective study, based on two lots of patients that underwent reconstructive surgical procedures of the BP. The first lot of patients includes right-handed individuals, that all had injuries on the right upper limb (the left cerebral hemisphere as dominant).
All the patients within this group had the surgical Oberlin procedure in common, as a surgical reconstructive attempt of restoring the elbow flexion.

A separate group of patients included patients with more complex injuries, either more complex cases, including a lesser compliance or adherence to long-time standardized rehabilitation protocols. Both groups of patients were followed-up in a retrospective manner, from neuro-electrodiagnosis point of view. The 2 lots were followed during 7 years, while addressing to the Medical Universitary Center Iași: either through the Clinical Rehabilitation Hospital (for rehabilitation strategies or electrodagnosis), either through the Rehabilitation and Kinetotherapy Facility within the Treatment Center from the “Gr. T. Popa” University, or through the Clinical Emergency Hospital “St. Spiridon” (for surgical evaluation), as well as by ambulatory regime for electroneuromyography.

All the investigated patients possess a long medical history since the moment of the plexus injury, with various and multiple surgical procedures, with a long and slow evolution. All the patients underwent rehabilitation procedures during the mentioned period, at variable time intervals, but standardized only within the first lot of patients.

In the personal part, I also illustrated two selected clinical cases, which we analyzed throughout the notions of cortical activity and psychomotor rehabilitation.

Alongside difficulties in following BP cases during the years, serious limitations were also present during the Sars-cov2 pandemics, which restricted clinical evaluations or electrodagnosis-based follow up.

The main purpose of the study is to find correlations between the lesions of the BP, surgical procedures and electrodagnosis findings, different postsurgical milestones, as well as interpret this data from the point of view of the cortical reactivity as a response to long term rehabilitation plans. Hence the combined clinical and electrophysiological approach we entitled as “neuro-electrophysiological correlations”.
Neuro-electrophysiological follow up study of brachial plexus lesions

Demographic data

22 patients (14 men, 8 women) with chronic, traumatic BP lesions, were divided in two lots, according to having received the Oberlin surgical procedure, on the same side (the patients from the first lot).

The second lot included a diverse collection of cases, consisting in both patients with affectation of the dominant limb, as well as the opposite one for other patients.

Both groups were followed up clinical and electrophysiological, after attending medical rehabilitation procedures.

Men are usually much more predisposed to BP trauma, especially in the age category of 20-39 years.

In both our lots, there was a much more frequent affectation of the dominant right upper limb (64%), in patients originating from urban environment (16 cases).

We observed a dynamic of incidence of BP palsies that suggests the young adult age, usually male, with trauma related to traffic accidents (13 out of the 22 cases), followed by traumatic circumstances related to professional activities or sports.

In the early stages of the injury, the microsurgical reconstructive procedures aim towards restoring the elbow flexion of the forearm against the arm, and the function of shoulder elevation. Surgery is usually planned according to EMG findings.

Following the initial surgical interventions, other reconstructive strategies may be necessary, sometimes palliative (most of our patients having undergone 2-4 surgeries).

Material and methods

The 22 patients with traumatic BP lesions were evaluated and monitored both clinically and from electrophysiological perspective.

11 patients included in the first lot had the Oberlin surgical technique in common (neurotization of fascicular motor group from the ulnar nerve). These patients were clinically assessed by the MRC scale and measurement of muscle strength, as well as by ENMG and TMS analysis, during a 6 months period (in the beginning and at 6 month’s endpoint).

During this time, they did rehabilitation therapy consisting in neuromuscular electrical stimulation (NEMS) and proprioceptive neuromuscular facilitation (PNF), 3 sessions/week.
The other 11 patients were only monitored by the same methods. These patients did not relate to the same dominant limb lesion level, nor to any form of standardized protocol.

All patients were assessed at various time intervals, after different surgical procedures meant to restore the upper limbs functionality, in diverse rehabilitations centers across the country.

The patients from the first lot had a mainly C5-C6/C7 affectation of the BP, while the ones from the second lot had either C5-C6/C7 or total BP lesions.

In the first group of patients, alongside the Oberlin procedure, the medical records and history of the patients revealed an often used procedure of neurotization of the spinal nerve to the suprascapular nerve, a technique also present among some of the patients in the second group, together with different muscle transpositions or tendon transfer procedures, or neurotization of intercostal nerves to the musculocutaneous nerve.

In all of these cases, one of the most frequent objectives of reconstructive microsurgery is to restore the elbow’s function, which explains the very frequent use of the Oberlin technique.

For the statistical significance, a criterion for assembling the first lot was also the particularity that the affected upper limb to also be the dominant one.

None of the monitored patients had any comorbidities that would in any way limit the access to the mentioned investigations. Especially related to the TMS investigations, there were no history of epileptic seizures and none of the patients had any pacemaker.

The EMG exam itself does not consist in any absolute contraindications (not even anticoagulant therapy, which was not the case).

We performed TMS with a Magstim Rapid® device (Magstim Co Ltd, Whitland, Dyfed, UK), with the “8” or “butterfly” shaped coil, having a medium diameter of 7 cm, which is able to generate a magnetic field up to 1.2 Tesla.

The nervous conduction studies and the needle EMG were performed on an EMG Neurosoft® device with 2 channels.

The dynamometric evaluation was realized by the use of a hydraulic Jamar® dynamometer.

For the determining of the motor threshold at the TMS investigation, the coil was positioned above the cerebral motor area (the projection of the upper limb), studying the response from the first dorsal interosseous (FDI), in conditions of muscle relaxation. However, since the motor deficit was significant, we used facilitation (minimal voluntary contraction of the investigated muscle). The stimulation was performed with 100% intensity (considering the increase of the peripheral latency).
During the procedure, we used surface electrodes positioned at FDI level (active) and on the 2\textsuperscript{nd} or 3\textsuperscript{rd} phalange (reference). The ground electrode was a bracelet type, attached to the forearm.

After recording MEP at cortical stimulation, we stimulated at cervical level, recording on FDI and BB, using the same “8”-shaped coil, in lateral-vertebral C7 incline position (in order to stimulate the nerve roots, not the spine).

The “8” or “butterfly” shaped coil was preferred instead of the circular one for its better propagation of the field. In this manner, we adapted the method which we usually use for central/ pyramidal tract pathology (cerebrovascular, multiple sclerosis etc.) to the current situation, in which we investigate the block or the delay in conduction towards the peripheral segment.

The ENMG study was designed to identify neurogenic modifications according to the patient’s history.

The statistical analysis was performed with STATISTICA 6.0 StatSoft (Europe). The comparison between the first and second evaluations was done by the t test, ANOVA analysis. The results were analyzed according to standard variation, in which $p<0.05$ is considered significant.

**Results**

**Follow up of the first lot**

Among the first lot, 5 patients were not compliant to the rehabilitation protocol (they invoked personal reasons). Even under these circumstances, all patients (including the 5) attended rehabilitation therapy during the first two weeks, and all patients showed up at the 6 months evaluation.

At the final evaluation, MEP latency decreased in the FDI and BB, both at cortical level (especially in the 6 patients with continuous protocol adherence), according to the data in table 6.11 and 6.12.

There were also improvements at the dynamometric testing. We considered normal values of 12KgF for women and 14 KgF for men.

The TMS data in the patients that continued rehabilitation throughout the period correlated with improvement on the MRC scale (in elbow flexion) and either variable amount of MUAP recruitment or an intensification of spontaneous pathological activity, recorded during the needle EMG exam.
Table 6.11 MEP latency at the first TMS evaluation

<table>
<thead>
<tr>
<th>Patient</th>
<th>Initial TMS</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>cerebral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>right</td>
<td>left</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MEP latency (ms)</td>
<td>21,5</td>
<td>26,2</td>
<td>0</td>
<td>14,5</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>17</td>
<td>25,7</td>
<td>44</td>
<td>15,5</td>
<td>54,5</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>16,2</td>
<td>27,1</td>
<td>36,9</td>
<td>13,8</td>
<td>34</td>
<td>14,5</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>16,1</td>
<td>29,5</td>
<td>29,7</td>
<td>18,7</td>
<td>31</td>
<td>19,5</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>17</td>
<td>28</td>
<td>0</td>
<td>17,2</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>17</td>
<td>28</td>
<td>26</td>
<td>15</td>
<td>27,8</td>
<td>15,5</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>16,2</td>
<td>27</td>
<td>31,2</td>
<td>15,5</td>
<td>34,1</td>
<td>16,2</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>21</td>
<td>31,2</td>
<td>29</td>
<td>17,1</td>
<td>31,2</td>
<td>17,5</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>16,5</td>
<td>29,2</td>
<td>35,1</td>
<td>16,1</td>
<td>36,5</td>
<td>16,5</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>17,3</td>
<td>27,6</td>
<td>37,1</td>
<td>16,2</td>
<td>39,2</td>
<td>16,6</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>14,5</td>
<td>0</td>
<td>15,2</td>
</tr>
</tbody>
</table>

Table 6.12 MEP latency at the second TMS evaluation

<table>
<thead>
<tr>
<th>Patient</th>
<th>TMS at 6 months endpoint</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>cerebral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>right</td>
<td>left</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MEP latency (ms)</td>
<td>21,5</td>
<td>25,8</td>
<td>28</td>
<td>14,5</td>
<td>29</td>
<td>15</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>17</td>
<td>21,3</td>
<td>32</td>
<td>15</td>
<td>43</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>16,2</td>
<td>23,8</td>
<td>31</td>
<td>13,8</td>
<td>32,1</td>
<td>14,5</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>15,6</td>
<td>26,3</td>
<td>25,1</td>
<td>18,3</td>
<td>26,2</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>17</td>
<td>26,9</td>
<td>35</td>
<td>17,2</td>
<td>39</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>16,7</td>
<td>25,2</td>
<td>22</td>
<td>15</td>
<td>24,8</td>
<td>15,4</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>15,5</td>
<td>23,1</td>
<td>26,2</td>
<td>15,5</td>
<td>30,1</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>21</td>
<td>29,2</td>
<td>27,8</td>
<td>17,1</td>
<td>29,8</td>
<td>17,5</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>16</td>
<td>24,1</td>
<td>31,8</td>
<td>16</td>
<td>32,1</td>
<td>16,5</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>17,3</td>
<td>27,1</td>
<td>36,3</td>
<td>16,2</td>
<td>37,9</td>
<td>16,6</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>17</td>
<td>29</td>
<td>37</td>
<td>17</td>
<td>38,3</td>
<td>17,5</td>
</tr>
</tbody>
</table>
On the MRC scale there were improvements from the value of 2 to 4 in the case of 2 patients, and from 3 to 4 in 2 other cases, as well as an improvement from 1 to 3 and from 3 to 4, respectively.

Even if 5 patients discontinued therapy, they also showed mild TMS ameliorations, nevertheless, without improvements of the other parameters (EMG or MRC scaling).

Only the 6 compliant patients showed an increase in muscle strength at dynamometric evaluation (figure 6.16).

The significant amelioration of the MEP latency, as measured at left cerebral hemisphere, in the 6 patients with better improvement (p<0.002), correlated with evidence of an increased spontaneous activity at the needle EMG examination (Fibs and Psws).

The electoneurographic parameters (measured during the nervous conduction examinations) also improved. Hence, CMAP and SNAP (especially measured in the radial nerve), showed discrete better amplitudes (p<0.0001), in correlation with the MRC scale (p<0.001), as well as with the dynamometric results (p<0.01)

The 5 patients that only committed to the initial rehabilitation protocol, also presented discrete TMS improvements, especially at the bicipital measurements (p<0.04) and FDI (p<0.05).

Although without correlations or statistical significance, we also observed a mild improvement of the SNAP latency in the superficial radial nerve (p<0.05), in the 5 mentioned.
Follow up of the second lot

The patients from the second lot, clinical cases of BP affectation either on the right or left, were assessed by the same parameters as the ones from the first lot, in a pure retrospective manner.

Since their first evaluation, until the final one, the amount of time was variable for this group, from 6 months up to 2 years. All the patients attended different rehabilitation protocols, in different ambulatory facilities or by hospitalization, for at least a 10 days protocol of treatment, or the ideal 10 days every 6 months.

The rehabilitation protocols included associations between NEMS, TENS, PNF, kinetotherapy or even balneary treatment (some patients found addressability towards balneological facilities).

MEP latencies at the TMS examination slightly improved in patients that managed to attend rehabilitation for repeated protocols, nevertheless, without adherence to any kind of standardized protocol for the mentioned period of time. SNAP amplitude increased mildly, as well as the amplitude of CMAP (non-specifically). These modifications, although non-significant, were more obvious in the patients that did more procedures over time. In three of the patients, the needle EMG examination showed an increase in the spontaneous pathological activity. Discrete better values were also present on the MRC scale (more likely appreciation of amelioration from the value of 0.5 to 1), which tend to correlate in these three, with mild muscle strength improvement at the dynamometric test (figure 6.22).

![Figure 6.22 Dynamometric evaluation of the patients in the 2nd lot (measured in KgF)](image)

These data do not correlate in terms of statistical significance, neither related to the whole lot of patients, or right compared to left BP lesions.
**Discussions**

The ENMG protocol related to the particularities of each case, knowing the long history of the patients, already in the state of chronic disabilities. None of the patients had any recent surgical interventions. I referred more to the radial nerve, which can be affected in various lesions: C5-C6, C5-C6/C7, C7 or C7-C8/T1, or may be sometimes spared. The median and the ulnar nerve determine the forearm’s flexion against the arm when using the MRC scale. In our chronic patients, with long history of elbow flexion and severe MRC affection, motor evaluation of these nerves doesn’t provide useful information.

During the TMS study protocol, for both routine examinations, as well as for establishing the spots where the MEP’s amplitude would be maximal (for the two highlighted clinical cases), we used the facilitation phenomenon in order to properly assess the motor area activation. The patients, because of the severely influenced MRC, usually use the spared muscles to perform lifting of the forearm/ limb, a reason for studying the radial nerve (more roots).

Traumatic BP lesions usually require multiple surgical techniques association. The best results of elbow flexion are obtained in C5-C6 lesions (Hébert-Blouin et al., 2012). Even so, sometimes patients may also need to benefit from other interventions, for other associated deficits, as in the situation of restoring the first finger’s opposition (Sakellariou et al., 2014b, Hébert-Blouin et al., 2012).

Considering the complexity of our cases, we included the TMS evaluation with the electrode situated on the FDI, for a more accurate correlation with the dynamometric evaluation. Usually, for the small muscles in the hand, the circular coil is preferred. However, anticipating the problematic peripheral latency, we chose the “butterfly” shaped coil for a better propagation of the stimulus. Unlike CNS pathologies, where the motor threshold is considered to be the minimal intensity for which the stimulus determines MEP (minimum 50 µV in at least 5 of 10 stimulations) (Bolbocean, 2011), we used maximal intensity. In some cases, the peripheral latencies were shorter at FDI than at BB. This fact is explained by the delay and traumatic/ reconstructive particularities at C5-C6/C7 level.

This study is not dedicated to the TMS method, but rather to multiple correlations between clinical facts (MRC and strength evaluation) and EMG + TMS (especially related to the latency parameter of MEP: peripheral and central, which we consider much more relevant for characterization of peripheral reinnervation).

Even if the value of CMCT may, in some cases, show a decrease dependent on the amelioration of latency, we considered it to be less useful in this peripheral affection, and only referred to it in the selected clinical
cases, as relevant for the follow up of MEP amplitude in order to monitor the expansion of the cortical area of the reinnervated segment.

Neurorehabilitation by physiotherapy plays a major role in the patient’s evolution (Belviso et al., 2020, Huang et al., 2021). NEMS and PNF are not effective only at peripheral level by improvement of the elbow’s flexion, but also sustain neuroplasticity (Huang et al., 2021, Belviso et al., 2020). This research allies with actual information provided by rehabilitation that sustain the idea that EMG and TMS can provide good monitoring of the rehabilitation process (Rossini et al., 2015).

According to Zinon Kokkalis et al, patients with bilateral BP traumatic lesions that attended an intensive rehabilitation program composed by electrostimulation and motility exercises of the fingers, obtained good reproductible results (Kokkalis et al., 2022). After 3 months of movement against gravity without resistance, the initial MRC increased from 3/5 to 4/5 (at the 4th month endpoint) and to 5/5 after one year, with unrestricted motility (Kokkalis et al., 2022). These results are similar to the results we obtained in patients with amelioration from the first lot.

The rehabilitation potential of electrostimulation may vary from modulating the motor function to reducing the severity of symptoms in cohorts of patients (Enoka et al., 2020). NMES currents can increase muscle strength on specific muscles, however, the most spectacular results are represented by the increase of strength in contralateral muscles (Enoka et al., 2020). The increase of contralateral strength also explains why the muscle strength improved in some of the patients in our lots of patients, that didn’t receive any recent surgical procedure, but did periodic rehabilitation sessions.

The principle underlying the NEMS procedure involves the generation of a strong electrical field nearby the motor axons of the peripheral nerves, that leads to the depolarization of the axonal membrane, therefore producing an action potential that will trigger a muscle contraction. For all that, in order for NEMS to be efficient, the peripheral nerve that reaches the targeted muscle should be intact, as well as the vascularization of the muscle to be competent, hence the good applicability especially in CNS disorders (Knutson et al., 2019). This phenomenon explains why for our patients, some of the results are stationary (nevertheless, without high specificity when reporting ourselves to a noncontinuous rehabilitation protocol).

PNF is a rehabilitation technique dedicated to help develop muscle strength, based on applying a mechanical resistance to the muscle contraction, with facilitation of contractile strength. PNF is recommended to patients with peripheral affection and significant loss of muscle strength (Fritz et al., 2008).

We consider that the association of NEMS + PNF determined the increase of MRC in the 6 patients from the first lot, in good correlation with amelioration of strength at the dynamometric testing and the
electrophysiological parameters. This is also applicable for the 3 patients from the second lot, the ones who presented improvements both on the MRC scale and the dynamometric testing.

Antagonist techniques used during PNF, especially the stabilizing inversion and the dynamic inversion, can be used to promote functional movements orientated to specific tasks, in order to stimulate the motor learning phenomenon (Chagas et al., 2021, Teodor, Claudiu, 2013).

By analyzing the 2 lots of patients, the main idea that results are that a sustained rehabilitation protocol, with long term adherence from the patients, improves the representation of the corporal segment at cortical level, with clinical favorable correspondent.

**Conclusions**

In the two lots, even in the patients without significant clinical amelioration, electrodiagnosis related signals suggest the potential of further amelioration, or at least, preservation of the current function, this way sustaining the need for a long-term rehabilitation program.

**Case study: psychomotoricity – neuroplasticity correlations in brachial plexus lesions**

**Introduction**

Psychomotoricity is a scientific domain that studies the motility of the human body in relation with both the inner world and the environment. It also deals with the possibilities of correct perception of surrounding items (Berdila et al., 2019). It describes an ongoing phenomenon among the CNS. In BP lesions, since deficit is considerably severe, it is very common that ideomotoricity (the mental projection of the movement to be realized and its proper action) is impaired as a result of alteration of the motor act.

During the dynamics of evolution of the lesions of BP, starting with initial Wallerian degeneration in the proximal region of the affected nerve, up to the first signs of muscle atrophy, all the cascade of physio pathological events will eventually impact the sensory-motor representation of the affected limb at the cortical level (Stamate, 1998, Lundborg, 2000).

**Selected clinical case of brachial plexus palsies**

The first case is represented by a male patient, with history of a traumatic event caused by falling from height, resulting into a complex and total affectation of the BP, by elongation in the superior plexus and avulsions
in the inferior region. The accident occurred at the age of 31, the patient had 44 years old at the moment of our first evaluation.

He presented a particular attitude of fallen shoulder, with a clinical picture that correlated ever since the beginning with the ENG exam: absence of electrophysiological response in the median, ulnar and radial nerves, up to Erb’s point and axillary level. All the surgical procedures during the years had been doubled by constant rehabilitation treatment, in different rehabilitation facilities, usually twice a year. He obtained (especially after the transfer of *lattisimus dorsi* to the tendon of the biceps brachii, intervention performed by Prof. Dr. Stamate in Iași) an easy abduction of the arm with discrete flexion of the fingers. This remains the best surgical result over a complicated history of interventions (most of the palliative) performed in different clinics across the country. The hypotonia and paresthesia (up to dysesthesia) persisted for a long period of time at fingers level.

Repeated ENMG examination over the years revealed a mild amelioration in time of the nervous conduction, especially sensorial responses in all three mentioned nerves, as well as motor conduction velocity and CMAP amplitude slightly better in the median and radial nerve. However, there was still no axillary measurable CMAP. The needle EMG examination showed chronic neurogenic pattern in all muscle territories, with complete denervation signs in the right deltoid muscle.

Other interventions were necessary throughout the medical history of the patient, such right fist arthrodesis, transposition of the *flexor carpi radialis* towards the dorsal side, tenorrhaphy to the common group of fingers II-IV extensor tendons, transposition to the anterior of the *extensor pollicis longus* and tenorrhaphy to *palmaris longus*. One last surgical intervention was the transposition of the 4th toe extensor’s tendon to the tendon of *flexor carpi ulnaris* in the attempt to restore the thumb’s opposition.

The second case is represented by a woman that suffered a car accident 17 years ago, being hit and dragged by a car. She also benefited from a series of surgical procedures, out of which the Carrol procedure (performed in Iași by Prof. Dr. Stamate) lead to results that persisted in time.

ENMG investigations had been performed over the years, as well, showing absence of electrophysiologic response in the first determinations for all the 3 main nerves, and mild ameliorations following different surgeries. She benefited from repeated rehabilitation programs, especially by recovery of the arm’s abduction, laterality and anterior projection of the arm (the best motor performance so far), but with chronic limitation of elbow flexion.

Brain mapping through TMS is based on realizing a map of different projections of the segments of the body. It is determined by the number of points on the motor cortex where MEP is obtained when stimulated (Bolbocean, 2011). The standardized stimulus used is usually
greater than the minimum to produce MEP. The coil is being moved above the surface of the skull, on various axis systems, usually from centimeter to centimeter, in order to record multiple MEP. This results into a map of potentials of different amplitudes. The maximal amplitude will be located in the center of the motor area and will decrease once moving to the peripheral areas. The spot in which the maximal amplitude was measured is considered to be the optimal point of the recording or the hot-spot. As we go to the peripheral regions, the number of neurons dedicated to a precise contractile function decrease. The cortical neurons that compose the corticospinal tract conduce the impulses towards the anterior horns of the spinal cord. Further, through the peripheral motor neuron, the impulse reaches the muscle (Lupescu et al., 2006).

**Material and methods**

The evaluations performed in both patients are according to the protocol already described. Unlike other patients from the two lots, more than the dynamometric evaluations and the MRC classification of elbow flexion, when performing TMS we assessed the results on a 4-axis system, by stimulating every 2 centimeters (as an adaptation to the technical particularities we had), above the motor area of the upper right limb (the left cerebral hemisphere, as both the patients were right handed with affectation on the right). This motor mapping exercise allowed us to observe the evolution of the values after rehabilitation.

**Results**

The parameters (dynamometric, MRC, SNAP and CMAP amplitudes, needle EMG aspect) remained stationary at the 2 evaluations in the case of the first patient.

8 months after the first evaluation (while doing kinetotherapy, NEMS and PNF), CMCT decreased from 10 ms to 7.9 ms.

The second patient only had mild, insignificant amelioration of parameters, especially the CMCT that improved from 11 ms (the first evaluation) to only 10.5 ms (at the second evaluation).

For the first patient, at the first evaluation, the values of the spots varied from a maximum of 1.08 mV at the hot-spot, to 0.69 mV nearby, down to 0.35 mV in the farthest spots, hence resulting the mapping from figure 7.11.

At the second evaluation (after 8 months of rehabilitation), the motor mapping modified as in figure 7.12.

It may be worth mention that the rehabilitation therapy was effectuated a month prior to the TMS reevaluation.
Figure 7.11 Mapping of the motor area of the first patient, first evaluation, in an antero-posterior (ant-post) and medio-lateral (med-lat) axis system, at the left hemisphere level. The amplitude of the potentials is measured in mV.

Figure 7.12 Mapping of the motor area of the first patient, second evaluation. Ant-post: antero-posterior direction; med-lat: medio-lateral direction. MEP’s amplitude measured in mV.

In the control evaluation, MEP values ranged between 1.49 mV at the hot-spot level, 1.17 mV in the vicinity and 0.89 mV in the most peripheral stimulation spots. Considering the color code, where the most orange area represents the hot-spot (well represented the central point in figure 7.11, its extension can be seen in the control evaluation (figure 7.12).

The maximal MEP was also obtained in the vicinity of the point where the MEP amplitude was maximal at the first examination, just as the immediately following value (0.89 mV) showed extension in the axis system,
towards the periphery. Larger amplitudes of the MEP overlap, suggesting expansion.

This resulted in a more extensive map, in which there is no longer the notion of a peak as a central point associated with a maximum amplitude, but rather a surface in the form of a plateau, representing a better activation of the motor cortical area, concurrent with the facilitation phenomenon.

These phenomena do not correlate with a visible or significant improvement in the other monitored parameters (neither in the ENMG examination, nor in the MRC staging, nor in the dynamometric assessment of muscle strength).

The second patient comes from the first study group. In her case, we are talking about the treatment protocol based on the NEMS and PNF protocol performed only in the beginning (10 days of treatment). The second evaluation was carried out 6 months after the completion of the recovery procedures.

The values of the MEP amplitude in her case, at the first examination, oscillate from a value of 1.35 mV at the level of the hot-spot, to 0.89 mV in its proximity and 0.45 mV the most peripheral, resulting in the motor map in figure 7.13.

![Figure 7.13 Mapping of the motor area for the second patient, at the first evaluation. Ant-post: antero-posterior direction; med-lat: medio-lateral direction. MEP’s amplitude is measured in mV.](image)

At the next evaluation at the hot-spot level, an amplitude of 1.98 mV is recorded, with extension in the vicinity, being followed by the maximum value of 1.4 mV, amplitude with extension towards the periphery of the area, where it is interspersed with values that decrease up to 0.9 mV (figure 7.14).
Figure 7.14 Mapping of the motor area, the second evaluation. Ant-post: antero-posterior direction; med-lat: medio-lateral direction. MEP’s amplitude is measured in mV.

The representational dynamics at the cortical level correlates with better values of MEP latencies and is also reflected by the improvement of the CMCT parameter, which improved discretely in direct relation to the decrease of peripheral latencies, in both patients: from 10 ms to 7.9 ms (the first patient) and from 11 ms to 10.5 ms (second patient).

**Discussions**

Chronic sensory-motor impairment, in a topographic pattern involving the brachial plexus, suggests either segmental demyelination or axonal disruption, sometimes both at multiple levels within the plexus. The degree of reduction in muscle strength is proportional to the number of axons affected, and pain and the abolition of kinesthetic sense often worsen the functional deficit. PB involvement can produce some of the most confusing patterns of motor, sensory and vegetative interest (Daia, 2022). On clinical examination, the loss of motor functions, evidence of osteotendinous areflexia or sensory deficits may not always follow a very specific pattern of root or nerve trunk involvement (Stamate, 1998, Daia, 2022).

Combined investigative methods, such as the one used by us in the present case, are at this time the only diagnostic options that can guide an accurate diagnosis, facilitating the opportunity for appropriate treatment. From the experience of our cases, but also in sync with the current state of knowledge, the ENMG exam correlates with muscle function, and together they are directly related to phenomena at the cortical level. The stationary aspect of the evaluated samples correlates between determinations made at different time intervals, however, in the investigated patients from the two
groups, there are signs of decreases in MEP latencies to TMS, so implicitly, the premise of a better cortical activity in connection with medical recovery.

Where, due to the motor deficit, a satisfactory facilitation cannot be achieved through muscle contraction, we appreciate the stimulation of cortical reactivity through a better propagation of the phenomenon called ideomotricity towards the activation of neighboring muscle areas, through nearby nerve branches, in order to generate MEP (sometimes even without significant movement of the limb).

In order to perform TMS in these two patients, we performed the stimulation at the level of the primary motor area for the representation of the upper limb. I used the butterfly shaped coil to be able to achieve maximum stimulation but also because I considered it was easier to identify the hotspot. The triggered stimulus followed the path of the pyramidal way, through the corona radiata, through the internal capsule, at the level of the brain stem (bulbar junction) and then through the cervical spinal route. After the junction with the peripheral motor neuron, the impulse traversed the nerve path distally, towards the muscle, more difficult. I used the FDI muscle to aid in the facilitation phenomenon, which I needed, as patients were unable to perform satisfactory muscle activation for proper forearm flexion on the arm.

It should be noted that this mapping exercise did not aim to highlight an already known correlation between the bicipital motor deficit and the cortical representation (which would have shown modestly), but from the perspective of the psychomotricity of the PB lesions, following how later the different surgical procedures associated and sustained recuperative treatment, through ideomotricity translated as activation of complementary muscle groups, the degree of cortical activation can be increased, this increase being compatible with the phenomenon of continuous neuroplasticity.

CMCT remains a parameter of interest in the diagnosis of some CNS pathologies, but for the peripheral segment we opted to closely study the peripheral latency, which is much more relevant for the present study.

The patients' history is long, marked by many repair strategies, both surgical and rehabilitation-based. When the injury is chronic, and the muscle shows signs of atrophy, recovery can be viewed from the perspective of long-term psychomotor training. The functioning of ideomotricity is based on the techniques of stimulating the affected muscles, respectively by stimulating the motor nerve component (simultaneously and proportionally with the density of the muscle fibers in the muscles to maintain a contractile potential, thus preventing, or where they are already present, stabilizing the atrophy phenomena). Therapeutic strategies can also target the sensitive component, by training tactile discrimination, thus improving perceptual-motor coordination, restoring stereognosis and implicitly reorganizing the representation of the affected segment of the body through maps at the cortical level.
In the plasticity of the motor cortex each muscle territory can have multiple cortical projections that can partially overlap. At the same time the different cortical regions communicate by means of a vast horizontal neural network. In the framework of cerebral plasticity, it is considered that precisely these horizontal connections can change during the learning or recovery process, thus inducing changes at the level of motor maps (Navarro et al., 2007, Bolbocean, 2011).

All these phenomena have a counterpart in the followed cases and explain the expansion of the MEP amplitudes in the control mapping. The TMS results suggest a modest but present dynamic, an aspect that at this moment of chronic damage can only be explained by the impact generated by the continuity of the recuperative protocol over time.

I believe that where the MEP amplitude values are close between the two patients, and the first patient tends to have mapping parameters similar to the patient's, although having a more pronounced motor and strength deficit, these advantages of cortical dynamics in his case can be placed in the context of younger age (44 years versus 58 years, at the time of first presentation), an important non-modifiable factor still to be taken into account in such studies.

The most complex part of the recovery of lost motor function is the reintegration of peripheral impulses at the cortical level, both from a sensory and motor point of view. Without kinetic and sensory feedback from the effectors, a loss of cortical control center function may occur over time. The function of the affected limb will thus be less represented at the level of the cortex, in this context functional rehabilitation is mandatory after the microsurgical intervention on the peripheral nerve(s). The lost cortical functions will have to be relearned, as part of the redesign approach at the level of the sensory-motor homunculus (Stamate, 1998). Hence the need for lengthy rehabilitation procedures.

Conclusions

The activity evaluated at TMS supports the need for rehabilitation treatment over time, aimed at improving the affected psychomotor components: ideomotricity, perceptual-motor coordination, laterality and body representation, as a foundation in maintaining a proven measurable potential of continuous neuroplasticity.

The fact that the data do not consistently and significantly correlate with each other calls instead for protocols applicable to larger groups of patients, including observational studies or extended clinical case series.
GENERAL CONCLUSIONS

1. Nerve regeneration has a degree of unpredictability related to the evolution of the function of the affected limb, but also related to the benefits brought by recovery strategies, which require a long time.
2. Neurotization of an injured nerve requires time for the cortical and subcortical centers to reintegrate the denervated territory.
3. The value of nerve conduction studies and needle EMG can be seen in the follow-up of a chronic brachial plexus injury, in relation to the evolution under recovery treatment.
4. Improvements in TMS parameters are not always accompanied by benefits related to improvement in motor deficit or increase in muscle strength.
5. In certain cases, the improvement of the electrophysiological parameters at the cortical level is also correlated with slight improvements of the motor deficit related to the flexion of the forearm on the arm or of the muscle strength during dynamometric evaluation, but only in cases where the patient is undergoing recovery treatment (NEMS, PNF) in the long term.
6. In certain situations, the improvements may mean improvements in the motor and sensory parameters in the electroneurographic examination, which, although they have statistical significance, this is limited both from the perspective of small groups of patients, but also due to the lack of better elbow flexion functionality.
7. Even in the case of a recovery that does not translate into great clinical benefits, sustained neuromotor rehabilitation programs stimulate over time the cerebral mechanisms of representational plasticity of the affected limb.
8. Motor mapping using TMS gives functional meaning to procedures aimed at improving psychomotor, especially ideomotricity and body representation.
9. A long-term recovery protocol may be favorable to the patient, even if it does not always correlate with better functionality of the affected limb.

ORIGINALITY ASPECTS OF THE THESIS

The understanding of the mechanisms involved in this traumatic pathology of the young adult through the prism of the correlations between the mentioned investigative components, but also from a psychomotor perspective in the cortical mapping exercise of the post-surgical functionality of the brachial plexus, is unique at this moment in the specialized literature.

Since psychomotricity actually means interdisciplinarity, this is the common denominator found in the collaboration between medical specialties: plastic surgery and reconstructive microsurgery, clinical neurology and electrodiagnostic, neuromotor rehabilitation.

The innovative contribution to the field of knowledge comes from the practicality of the methods used, the leaning towards psychomotor
rehabilitation being by no means a field of theorizing, but aiming at the application of mechanisms for the benefit of the suffering ones.

The presented study is original by decoding the motor deficit and its impact from the perspective of the notions of cortical reactivity, long time after the moment of the trauma. Thus, we were able to translate into data how the ideomotricity affected in these plexopathies leads to the alteration of the cortical representation of the affected segment, but I also proved that the ideomotricity can also be stimulated by the recuperative program in order to stimulate the restoration of the correspondence between the peripheral and the central.

The presented research is, by these aspects, innovative also by monitoring the adaptability of the patient from the perspective of the notions of compliance, respectively non-compliance, to a recuperative program. This is evaluated in relation to non-modifiable factors of plexus injuries, such as the severity of the motor deficit, but also age.

**PERSPECTIVES OPENED BY THE THESIS**

The perspective that active mechanisms remain at the cortical level, even if the body segment represented at that level presents an important disability, is promising and encouraging for future innovations in medicine.

Maintaining these active areas through neuromotor rehabilitation therapies, even if clinically significant results are not seen in the long term, especially in elbow flexion, is a promising notion.

The concept of psychomotricity is actual, as a substrate of recuperative protocols, with implications and applicability in numerous medical and psychosocial fields. At the border between multiple specialties, psychomotricity is the common notion that harmoniously combines the peripheral and central notions of the individual viewed as a whole with the aim of the most harmonious functionality.

The results of this paper will modulate the discipline of Psychomotricity within the Faculty of Balneophysiotherapists, by improving the lessons on plexopathies and traumatic pathology of the peripheral nervous system in relation to the dynamics of cortical reactivity, helping students to become more oriented physiotherapists. The work will thus contribute to an improvement of the didactic material of this discipline from a practical perspective, through an impulse to develop its concepts with applicability in medical sciences.

The thesis also provides accessibility and visibility at international congresses and conferences, with information exchanges and refinements, from which patients can directly benefit.
SELECTIVE BIBLIOGRAPHY


Bolbocean O. *Aportul stimulării magnetice transcorticale la diagnosticul și urmărirea evoluției pacienților cu scleroză multiplă.* Universitatea de Medicină și Farmacie „Gr. T. Popa” Iași, 2011.


Sakellariou VI, Badilas NK, Stavropoulos NA et al. Treatment options for brachial plexus injuries. ISRN Orthop. 2014b Apr 14; 2014:314137.
