Clinical Neurophysiology xxx (xxxx) xxx

Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Changes in the thalamocortical component of high frequency oscillations following botulinum toxin treatment in cervical dystonia

Alessandro Cruciani [a,b], Gaia Anzini [a,b], Alessandro Magliozzi [a,b], Gabriella Musumeci [a,b], Daniel T. Corp [c,d], Maria Concetta Altavista [e], Vincenzo Di Lazzaro [a,b], Massimo Marano [a,b,*]

[a] Department of Medicine and Surgery, Unit of Neurology, Neurophysiology, Neurobiology, and Psychiatry, Università Campus Bio-Medico di Roma, Via Alvaro del Portillo, 21, 00128 Roma, Italy
[b] Fondazione Policlinico Universitario Campus Bio-Medico, Via Alvaro del Portillo, 200, 00128 Roma, Italy
[c] Turku Brain and Mind Center, Clinical Neurosciences, University of Turku, Turku, Finland
[d] Cognitive Neuroscience Unit, School of Psychology, Deakin University, Geelong, Australia
[e] Neurology Unit, San Filippo Neri hospital, ASL RM1, Rome, Italy

ARTICLE INFO

Keywords:
HFOs
BoNT-A
Cervical dystonia
Somatosensory pathway
Dystonia treatment

ABSTRACT

Objective: This study aims to investigate the central effects of Botulinum toxin type A (BoNT-A) on the somatosensory system in patients with cervical dystonia (CD), focusing on the thalamocortical pathway using high-frequency oscillations (HFOs) and short-latency afferent inhibition (SAI).
Methods: An observational longitudinal study was conducted on 10CD patients and 10 healthy controls (HC). HFOs and SAI were assessed for CD and HC at baseline (T0; the day before BoNT-A treatment). Then only for CD patients, SAI and HFOs were assessed again 30 days after (T1) BoNT-A treatment. Changes in SAI values and HFO early and late area between T0 and T1 in CD patients were evaluated with the Wilcoxon signed-rank test.
Results: At T0, CD patients exhibited significantly reduced early HFOs compared to HC, with no significant differences in late HFOs or SAI values. After BoNT-A treatment, a significant increase in early HFOs was observed in CD patients at T1, while late HFOs and SAI values remained unchanged.
Conclusion: The findings suggest that BoNT-A treatment may have central effects on thalamocortical activity, as evidenced by changes of early HFOs in CD patients following injections.
Significance: This study provides neurophysiological evidence supporting the central effects of BoNT-A on the somatosensory system and corroborates the idea of a somatosensory involvement in CD pathogenesis. This funding could pave the way for future integrated treatment approaches.

1. Introduction

In the past few decades, researchers and clinicians have focused their attention on the sensory system's contribution to the pathogenesis of focal dystonia (Conte et al., 2019). Patients with cervical dystonia (CD) complain of sensory symptoms, such as neck pain, even before the clinical disease onset. Additionally, clinical evidence supports that sensory abnormalities contribute to the pathogenesis of focal dystonia, as also suggested by the sensory trick phenomenon in CD (Conte et al., 2019; Corp et al., 2019). Currently, the most accessible and effective treatment for CD is botulinum toxin type A (BoNT-A) injection there. Given new insights into disease pathogenesis, some researchers have proposed that BoNT-A may have central effects other than the already known peripheral muscular action (Rosales and Dressler, 2010). High-frequency oscillations (HFOs) and short-latency intracortical inhibition (SAI) are two reliable neurophysiological measures that allow in vivo study of the somatosensory system, especially the thalamocortical pathway and sensorimotor integration (Cruciani et al., 2024; Tokimura et al., 2000). SAI is a neurophysiological test that probes the effects of afferent inputs on the primary motor cortex (M1) (Tokimura et al., 2000). HFOs are fast oscillations evoked by stimulation of sensory nerves composed of an early component (Early HFOs) and a late component (Late HFOs), appearing before or after the N20 wave peak respectively (Ozaki and Hashimoto, 2011). The early component is

* Corresponding author at: Department of Medicine and Surgery, Unit of Neurology, Neurophysiology, Neurobiology, and Psychiatry, Università Campus Bio-Medico di Roma, Via Alvaro del Portillo, 21, 00128 Roma, Italy.
E-mail address: m.marano@policlinicocampus.it (M. Marano).

https://doi.org/10.1016/j.clinph.2025.03.048
Accepted 27 March 2025
Available online 20 April 2025

thought to be generated by thalamo-cortical projections, while the late component is produced by cortical interneurons (Cruciani et al., 2024; Gobbelé et al., 2003; Restuccia et al., 2002). Therefore, in this study, we aim to use HFOs and SAI to investigate the effects of BoNT-A treatment on the somatosensory system in patients with CD.

2. Methods

2.1. Study design

We designed an observational longitudinal study to evaluate HFOs and SAI in CD patients just before and 30 days after BoNT-A treatment. The day before the expected BoNT-A injection was used as baseline (T0). At T0 we evaluated SAI, somatosensory evoked potentials (SEP) from the dominant hemisphere (i.e. left hemisphere for a right handed person) and we collected clinical data using the Toronto Western Spasmodic Torticollis Rating Scale (TWSTRS) (Boyce et al., 2012). We performed the same protocol for healthy controls (HC). Patients were retested 30 days after the BoNT-A treatment (T1) using the same approach. The study adhered to the Declaration of Helsinki and received approval from the local ethics committee. We used the STROBE checklist when writing our report.

2.2. Studied population

We enrolled 10 consecutive CD patients from the Movement disorder outpatient clinic of Fondazione Policlinico Universitario Campus Bio-Medico Hospital and San Filippo Neri Hospital both located in Rome during the period between January 2023 and January 2024. HC subjects (n = 10) were also recruited. All the participants provided written informed consent, none of the subjects had contraindications to transcranial magnetic stimulation (TMS) (Rossi et al., 2021). All the participants were right-handed, with handedness assessed through the Edinburgh handedness Inventory (Oldfield, 1971).

2.3. SEPs recording and HFOs extraction

SEPs were recorded following median nerve stimulation at the dominant wrist using a high-voltage stimulator (DS7A, Digitimer Ltd, UK). Bar electrodes were used, with the anode placed on the wrist crease and the cathode positioned proximally. In total, 1200 pulses of 200 μs duration were delivered at a frequency of 3.1 Hz. The stimulation intensity was individually adjusted to elicit a slight thumb twitch. This ensured that we were in the correct position for median nerve stimulation, and that the chosen intensity was not perceived as uncomfortable or painful by the subjects. Ag/AgCl surface electrodes were placed at the left CP3 (active electrode) and Fz (reference electrode) locations according to the international 10/20 system. SEPs were digitized at a 5 kHz sampling rate using a portable amplifier (BrainAmp MR plus, Brain Products GmbH, Germany, Version 1.10), bandpass filtered (0.5–2000 Hz), and exported using BrainVision Analyzer software (Brain Products GmbH, Germany, Version 1.05.0005). All traces were visually inspected by a board-certified neurologist before averaging to determine N20 latency and amplitude. We developed, validated, and applied semi-automatic MATLAB (The MathWorks, Inc., Massachusetts, USA, Version: R2020b) code to identify HFOs and characterize their features (Cruciani et al. 2024). In brief, the data is filtered using a 400–800 Hz Butterworth filter and then rectified. The onset of the HFO is identified as the point at which the upward deflection of the rectified data exceeds 50 % of the background activity, while the HFO offset is defined as the point when this deflection returns to less than 50 % of the background activity. Background activity is determined from the rectified wave within a suitable interval of the pre-stimulus epoch. The HFO area is initially calculated from the rectified data between the onset and offset points, after which the area of the background noise is subtracted. The “Early” and “Late” areas are defined relative to the N20 peak latency. The individual frequency is extracted using the same code. The latency and amplitude of the N20 were visually verified with BrainVision Analyzer (BrainProducts).

2.4. Short latency afferent inhibition

TMS was performed using a Magstim 200 Stimulator (Magstim Co, Whitland, UK) with a standard figure-of-eight 70 mm coil, oriented to produce a posterior-anterior current flow at the cortical level approximately perpendicular to the motor strip. The motor hotspot for the First Dorsal Interosseous (FDI) muscle was identified as the scalp location yielding the highest amplitude and the most consistent Motor Evoked Potentials (MEPs) in the relaxed FDI at the lowest stimulation intensity. Resting Motor Threshold (RMT) and Active Motor Threshold (AMT) were defined following international guidelines (Rossini et al., 2015). We then adjusted the TMS stimulus in order to evoke an EMG response in the relaxed FDI of 1 mV peak-to-peak (Di Lazzaro et al., 2005). Surface muscle responses from the dominant hand’s FDI muscle were recorded using two Ag/AgCl electrodes in a belly/tendon montage. These muscle responses were amplified (sampling rate 2048 Hz) and filtered (bandwidth 3–3000 Hz) using D150 amplifiers (Digitimer, Welwyn Garden City, Hertfordshire, UK). Data were collected on a computer and stored for later analysis with a CED 1401 A-D converter (Cambridge Electronic Design, Cambridge, UK). Short-latency afferent inhibition (SAI) is produced by sensory inputs (conditioning stimulus or CS), that at specific interstimulus intervals (ISIs), inhibit motor responses evoked by TMS (test stimulus or TS) in a target muscle (Tokimura et al., 2000). In our study, the CS consisted of single electrical pulses (200 ms) delivered using the same procedure as for SEPs recording. Electrical stimulation was applied to the wrist of the dominant hand, at the same location and at the same intensity as for SEPs. Median nerve stimulation was paired with TMS of the contralateral motor cortex. ISIs were determined based on the individual N20 latency. SAI was tested at interstimulus interval corresponding to N20 latency plus 2 and 4 ms (ISIs 2 and ISIs 4, respectively), ensuring that magnetic stimuli were delivered 2 and 4 ms after the arrival of somatosensory inputs to S1.

2.5. Statistical analysis

Statistical analysis was conducted using SPSS 25.0 (IBM Corp.,USA) and GraphPad Prism 5.0. Due to date non-normal distribution, the differences in SAI and HFO values between HC and CD patients at T0 were assessed using the Mann-Whitney *U* test. Changes in SAI values and HFO early and late area between T0 and T1 in CD patients were evaluated with the Wilcoxon signed-rank test. Bonferroni correction was applied for multiple comparisons when appropriate. Spearman’s correlation was performed to assess potential correlation between clinical and neurophysiological measures.

3. Results

10 CD patients and 10 HC were included; demographic and clinical

Table 1
Clinical and demographic characteristics of the studied population expressed by median [Interquartile range].

		CD patients	HC
Sex	M	5	4
	F	5	6
Age (years) [IQR]		50 [11]	44 [9,25]
TWSTR (total value) [IQR]	T0	20 [11]	–
	T1	11 [11,5]	–

CD: cervical dystonia patients; HC: healthy controls; TWSTR: Toronto Western Spasmodic Torticollis Rating Scale; M: male; F: female.

characteristics are summarized in Table 1 and Supplementary table 1. During the study period, no patients were taking any medications that could potentially affect the neurophysiological methods. All data are reported as median values (interquartile range [IQR]). There was no significant difference in age between the CD and the HC groups (median = 50 years [IQR = 11], 44 years [9,25], respectively). There was a statistical significance improvement of the TWSTR after the treatment (20 [11] vs 11 [11,5], $p < 0,001$). Overall, Spearman's correlation didn't show any statistically significant correlation between clinical and neurophysiological measures.

3.1. HFOs

At T0, Early HFO area was significantly smaller in CD patients when compared with HC (0,36 μV^2 [0,37] vs 1.43 μV^2 [0,53]; $p < 0.001$), while no significant differences were observed for late HFOs AUC (0,42 μV^2 [0,47] vs 0,72 μV^2 [0,64]; $p = 0.436$) (Fig. 1). Additionally, comparisons of T0 and T1 values in CD patients revealed a statistically significant increase in Early HFOs AUC values at T1 compared to T0 (0,62 μV^2 [0,54] vs 0,36 μV^2 [0,47]; $p = 0.028$). Comparison between Late HFOs AUC values between T1 and T0 did not show a statistically significant change (0,72 μV2 [0,64] vs 0,32 μV2 [0,20]; $p = 0,333$). No other differences were found (Table 2).

3.2. SAI values

We then compared mean SAI values for the two studied intervals (2 ms and 4 ms) at baseline between CD patients and HC. Inhibition of MEPs after SAI protocol at baseline was higher in HC than in CD patients but this difference did not reach statistical significance (0.27 [0,29] vs 0,4 [0,41]; $p = 0.393$) (Fig. 2). MEPs inhibition remains stable in CD patients between T1 and T0 (0,4 [0,22] vs 0,4 [0,41]; $p = 0,821$).

Table 2
HFOs early and late components expressed by median [Interquartile Range] at baseline (T0) and after 30 days from BoNT-A treatment (T1).

		T0	T1
HFOs Early AUC (μV2) [IQR]	CD patients	0,35 [0,37]	0,62 [0,54]
	HC	1,43 [0,53][0,53]	––
HFOs Late AUC (μV^2) [IQR]	CD patients	0,72 [0,64]	0,32 [0,20]
	HC	0,42 [0,47] [0,47]	––
N20 latency (ms) [IQR]	CD patients	20 [2]	21 [2]
	HC	19,5 [2,2] [2,2]	––
SAI 2–4 (% of test MEP) [IQR]	CD patients	0,4 [0,41]	0,4 [0,22]
	HC	0,27 [0,29][0,29]	––

AUC: area under the curve; HFOs: High-frequency oscillations; SAI: short-afferent inhibition; CD: cervical dystonia; HC: healthy controls.

4. Discussion

Our study supports the notion that BoNT-A treatment has a central effect, specifically showing the ability to restore pathological communication between the thalamus and the somatosensory cortex. At baseline, CD patients exhibited abnormal thalamo-cortical activity, as evidenced by a significant reduction in the Early HFOs area. Following BoNT-A treatment, the Early HFOs area increased. Further evidence in favour of a central effect of BoNT-A treatment has been provided by magnetic resonance imaging (MRI) findings (Nevrlý et al., 2018). In this study, twelve patients with CD who were naïve to BoNT-A and twelve HC underwent functional MRI (fMRI) at baseline and then again four weeks after their first BoNT-A treatment. The results indicated increased

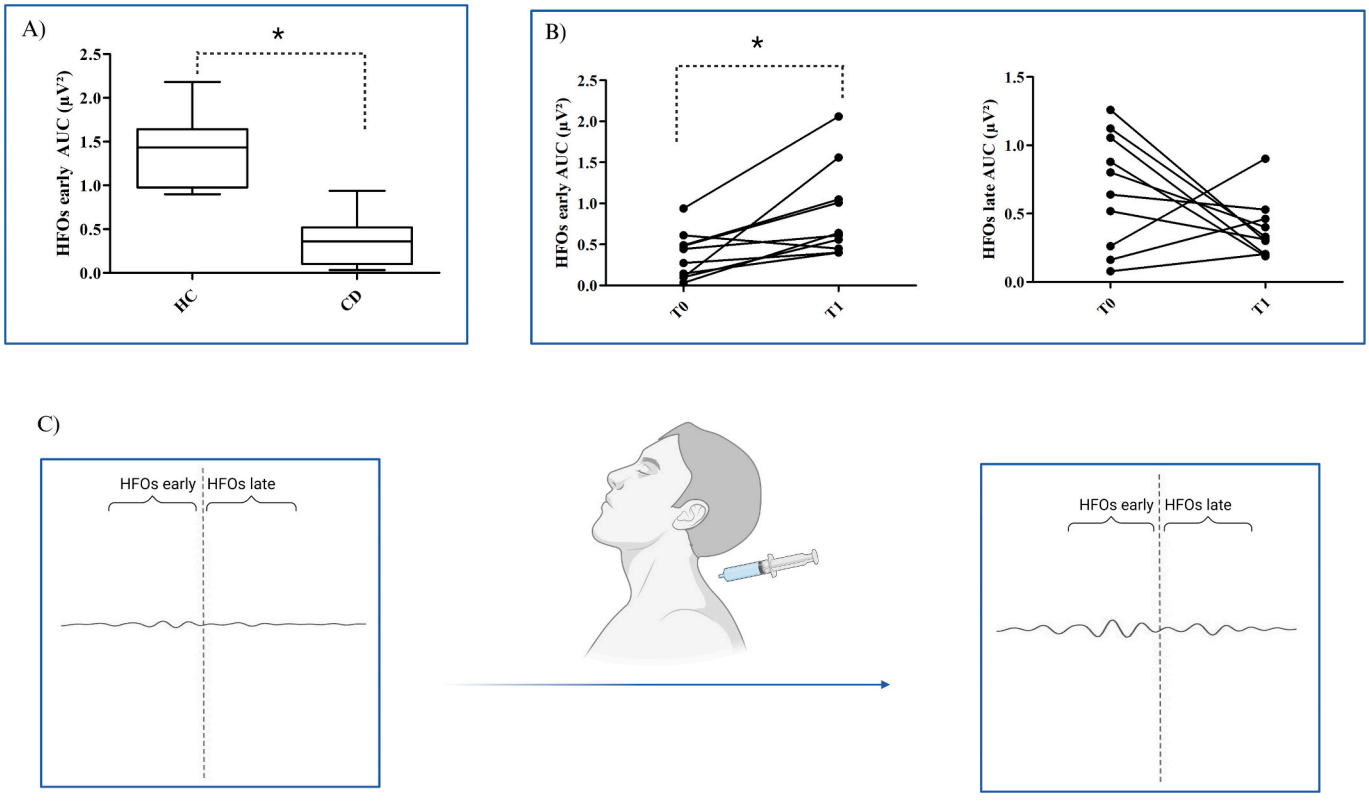

Fig. 1. HFOs early component was statistically significantly lower in CD patients than in HC. Moreover, HFOs early component in CD patients increased after 30 days from BoNT-A injection. Upper panel (A): HFOs early AUC at baseline was statistically significantly lower in CD patients compared to HC. Upper panel (B): HFOs early AUC and late AUC at baseline (T0) and after 30 days of BoNT-A injection (T1). There is a statistically significant increase of the HFOs early AUC between T0 and T1. Lower panel (C) Representative HFOs AUC at T0 and T1 from Subject 2. HFOs: High-frequency oscillation; AUC: Area under the curve; CD: cervical dystonia; HC: healthy controls.

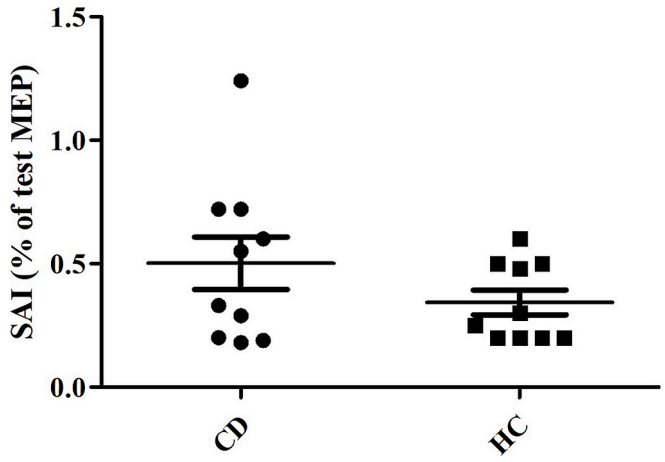

Fig. 2. Baseline (T0) SAI values of CD patients and HC. We found no statistically significance differences. SAI: Short-afferent inhibition; CD: cervical dystonia; HC: healthy controls; MEP: motor evoked potentials.

activation in various structures of the somatosensory pathway, including the thalamus, following treatment (Nevrlý et al., 2018). Those results follow previous fMRI evidence in which an impaired activation of somatosensory pathways of both cortical and deep structures – i.e. thalamus – have been found in CD patients (Opavský et al., 2011). Additionally, neurophysiological studies have been conducted to assess the central effects of BoNT-A in patients with dystonia. Specifically, a neurophysiological study in a cohort of patients with upper limb dystonia revealed impaired inhibition, as measured by the short-latency intracortical inhibition (SICI) protocol, compared to healthy subjects (Gilio et al., 2000). One month after BoNT-A treatment, these patients exhibited test response inhibition comparable to that of healthy subjects, suggesting a cortical effect of BoNT-A treatment (Gilio et al., 2000). Our findings reinforce these results and provide a more cost-effective and widely accessible method to assess the effects of BoNT-A treatment on the somatosensory system.

In our study, baseline early HFOs were significantly smaller than those of healthy controls. HFOs are fast oscillations ranging between 80 and 600 Hz widely used in the study of neurological conditions (Ozaki and Hashimoto, 2011). Traditionally, we classified HFOs into spontaneous and evoked, with the spontaneous further divided into physiological and pathological (Zijlmans et al., 2012). On the other hand, the importance of evoked HFOs as a biomarker of different neurological conditions has significantly increased in the last decades. Indeed, evoked HFOs have been found altered in many neurological conditions such as myoclonic epilepsy, multiple sclerosis, amyotrophic lateral sclerosis, and in cervical dystonia (Capone et al., 2020; Dubbioso et al., 2022; Hamada et al., 2007; Inoue et al., 2004). Our results align with previous research that identified an alteration in the Early HFOs component when comparing dystonic patients to healthy subjects (Inoue et al., 2004). The altered thalamo-cortical component of HFOs in dystonic patients may provide valuable insights into inhibitory mechanisms. Therefore, studies involving experimental rat models have clearly shown a loss of striatal parvalbumin-reactive GABAergic neurons (Gernert et al., 2000) that could partially explain the HFOs alteration seen in these patients.

Another interesting point comes from the results of SAI tested at baseline for CD patients and HC. Indeed, we found no differences in terms of MEPs afferent inhibition between CD patients and HC at baseline. The literature regarding the modification of MEPs in response to a conditioning stimulus in CD patients is contrasting. Indeed, Abbruzzese and colleagues found impaired MEPs facilitation using long ISIs (200–1000 ms) (Abbruzzese et al., 2001). Moreover, Tamburin and coworkers evaluate changes in MEPs using cutaneous digital stimulation as a conditioning stimulus (Tamburin et al., 2002). They found a topographic alteration of this inhibition when compared to healthy people (Tamburin et al., 2002). These results could be explained by methodological differences between the studies (i.e. Long latency afferent inhibition vs Short latency afferent inhibition; cutaneous stimulation of the finger vs wrist stimulation). Finally, the fact that SAI values in our study are normal compared to HC emphasizes that the alteration in the somatosensory pathway appears to arise from deep structures like the thalamus with limited involvement of the cortex.

5. Limitations

This study presents some limitations. Firstly, the sample size. Nevertheless, other studies on CD have achieved interesting results using similar sample sizes (Inoue et al., 2004; Nevrlý et al., 2018). Secondly, the lack of a neuroimaging correlates that could help us to better understand the neurophysiological parameters prevent us to draw more robust conclusions. Accordingly, multicentric study with a greater sample-size and neuroimaging evaluation is needed to confirm our preliminary results.

6. Conclusion

In conclusion, this study provides neurophysiological evidence of possible effects of BoNT-A treatment on the somatosensory pathway, particularly on thalamo-cortical projections. Given the recent evidence highlighting the ability of certain neurophysiological techniques—such as transcranial alternating current stimulation (tACS)—to modulate the thalamocortical component of HFOs (Cruciani et al., 2024), these results could pave the way for future integrated therapeutic approaches.

CRediT authorship contribution statement

Alessandro Cruciani: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. **Gaia Anzini:** Data curation, Investigation, Writing – review & editing. **Alessandro Magliozzi:** Data curation, Investigation, Validation, Writing – review & editing. **Gabriella Musumeci:** Data curation, Investigation, Methodology. **Daniel T. Corp:** Data curation, Methodology, Writing – original draft, Writing – review & editing. **Maria Concetta Altavista:** Data curation. **Vincenzo Di Lazzaro:** Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Massimo Marano:** Conceptualization, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding

No specific funding was received for conducting this study.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: There are no direct potential conflict of interest for this specific research. General competing interest: AC: travel grants and/or speaking honoraria from Merck, Brystol-Meyer-Squid and Sanofi; GA: no conflict of interest; AM: no conflict of interest; GM: no conflict of interest; DTC: No conflict of interest; VDL: no conflict of interest; MM: received speaker honoraria and consultancies by Medtronic, Piam, Sanofi, Zambon, Bial, Lusofarmaco.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clinph.2025.03.048.

References

Abbruzzese, G., Marchese, R., Buccolieri, A., Gasparetto, B., Trompetto, C., 2001. Abnormalities of sensorimotor integration in focal dystonia: a transcranial magnetic stimulation study. Brain 124, 537–545. https://doi.org/10.1093/brain/124.3.537.

Boyce, M.J., Canning, C.G., Mahant, N., Morris, J., Latimer, J., Fung, V.S.C., 2012. The Toronto Western spasmodic torticollis rating scale: reliability in neurologists and physiotherapists. Parkinsonism Relat Disord 18, 635–637. https://doi.org/10.1016/j.parkreldis.2012.02.007.

Capone, F., Motolese, F., Rossi, M., Musumeci, G., Insola, A., Di Lazzaro, V., 2020. Thalamo-cortical dysfunction contributes to fatigability in multiple sclerosis patients: A neurophysiological study. Multiple Sclerosis and Related Dis 39, 101897. https://doi.org/10.1016/j.msard.2019.101897.

Conte, A., Defazio, G., Hallett, M., Fabbrini, G., Berardelli, A., 2019. The role of sensory information in the pathophysiology of focal dystonias. Nat Rev Neurol 15, 224–233. https://doi.org/10.1038/s41582-019-0137-9.

Corp, D.T., Joutsa, J., Darby, R.R., Delnooz, C.C.S., van de Warrenburg, B.P.C., Cooke, D., et al., 2019. Network localization of cervical dystonia based on causal brain lesions. Brain 142, 1660–1674. https://doi.org/10.1093/brain/awz112.

Cruciani, A., Pellegrino, G., Todisco, A., Motolese, F., Sferruzzi, M., Norata, D., et al., 2024. High-frequency transcranial alternating current stimulation matching individual frequency of somatosensory evoked high-frequency oscillations can modulate the somatosensory system through thalamocortical pathway. Cereb Cortex 34, bhad481. https://doi.org/10.1093/cercor/bhad481.

Di Lazzaro, V., Pilato, F., Dileone, M., Tonali, P.A., Ziemann, U., 2005. Dissociated effects of diazepam and lorazepam on short-latency afferent inhibition. J Physiol 569 (Pt 1), 315–323. https://doi.org/10.1113/jphysiol.2005.092155.

Dubbioso, R., Striano, P., Tomasevic, L., Bilo, L., Esposito, M., Manganelli, F., et al., 2022. Abnormal sensorimotor cortex and thalamo-cortical networks in familial adult myoclonic epilepsy type 2: pathophysiology and diagnostic implications. Brain Commun 4, fcac037. https://doi.org/10.1093/braincomms/fcac037.

Gernert, M., Hamann, M., Bennay, M., Löscher, W., Richter, A., 2000. Deficit of striatal parvalbumin-reactive GABAergic interneurons and decreased basal ganglia output in a genetic rodent model of idiopathic paroxysmal dystonia. J Neurosci 20, 7052–7058. https://doi.org/10.1523/JNEUROSCI.20-18-07052.2000.

Gilio, F., Currà, A., Lorenzano, C., Modugno, N., Manfredi, M., Berardelli, A., 2000. Effects of botulinum toxin type A on intracortical inhibition in patients with dystonia. Ann Neurol 48, 20–26.

Gobbelé, R., Waberski, T.D., Thyerlei, D., Thissen, M., Darvas, F., Klostermann, F., et al., 2003. Functional dissociation of a subcortical and cortical component of high-frequency oscillations in human somatosensory evoked potentials by motor interference. Neuroscience Lett 350, 97–100. https://doi.org/10.1016/S0304-3940(03)00877-2.

Hamada, M., Hanajima, R., Terao, Y., Sato, F., Okano, T., Yuasa, K., et al., 2007. Median nerve somatosensory evoked potentials and their high-frequency oscillations in amyotrophic lateral sclerosis. Clin Neurophysiol 118, 877–886. https://doi.org/10.1016/j.clinph.2006.12.001.

Inoue, K., Hashimoto, I., Shirai, T., Kawakami, H., Miyachi, T., Mimori, Y., et al., 2004. Disinhibition of the somatosensory cortex in cervical dystonia-decreased amplitudes of high-frequency oscillations. Clin Neurophysiol 115, 1624–1630. https://doi.org/10.1016/j.clinph.2004.02.006.

Nevrlý, M., Hluštík, P., Hok, P., Otruba, P., Tüdös, Z., Kaňovský, P., 2018. Changes in sensorimotor network activation after botulinum toxin type A injections in patients with cervical dystonia: a functional MRI study. Exp Brain Res 236, 2627–2637. https://doi.org/10.1007/s00221-018-5322-3.

Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9, 97–113. https://doi.org/10.1016/0028-3932(71)90067-4.

Opavský, R., Hluštík, P., Otruba, P., Kaňovský, P., 2011. Sensorimotor network in cervical dystonia and the effect of botulinum toxin treatment: A functional MRI study. J Neurol Sci 306, 71–75. https://doi.org/10.1016/j.jns.2011.03.040.

Ozaki, I., Hashimoto, I., 2011. Exploring the physiology and function of high-frequency oscillations (HFOs) from the somatosensory cortex. Clin Neurophysiol 122, 1908–1923. https://doi.org/10.1016/j.clinph.2011.05.023.

Restuccia, D., Valeriani, M., Grassi, E., Mazza, S., Tonali, P., 2002. Dissociated changes of somatosensory evoked low-frequency scalp responses and 600 Hz bursts after single-dose administration of lorazepam. Brain Res 946, 1–11. https://doi.org/10.1016/s0006-8993(02)02818-4.

Rosales, R.L., Dressler, D., 2010. On muscle spindles, dystonia and botulinum toxin. Eur J Neurol 17, 71–80. https://doi.org/10.1111/j.1468-1331.2010.03056.x.

Rossi, S., Antal, A., Bestmann, S., Bikson, M., Brewer, C., Brockmöller, J., et al., 2021. Safety and recommendations for TMS use in healthy subjects and patient populations, with updates on training, ethical and regulatory issues: Expert Guidelines. Clin Neurophysiol 132, 269–306. https://doi.org/10.1016/j.clinph.2020.10.003.

Tamburin, S., Manganotti, P., Marzi, C.A., Fiaschi, A., Zanette, G., 2002. Abnormal somatotopic arrangement of sensorimotor interactions in dystonic patients. Brain 125, 2719–2730. https://doi.org/10.1093/brain/awf279.

Tokimura, H., Di Lazzaro, V., Tokimura, Y., Oliviero, A., Profice, P., Insola, A., et al., 2000. Short latency inhibition of human hand motor cortex by somatosensory input from the hand. J Physiol 523 (Pt 2), 503–513. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00503.x.

Zijlmans, M., Jiruska, P., Zelmann, R., Leijten, F.S.S., Jefferys, J.G.R., Gotman, J., 2012. High-frequency oscillations as a new biomarker in epilepsy. Ann Neurol 71, 169–178. https://doi.org/10.1002/ana.22548.

Rossini, P.M., Burke, D., Chen, R., Cohen, L.G., Daskalakis, Z., Di Iorio, R., Di Lazzaro, V., Ferreri, F., Fitzgerald, P.B., George, M.S., Hallett, M., Lefaucheur, J.P., Langguth, B., Matsumoto, H., Miniussi, C., Nitsche, M.A., Pascual-Leone, A., Paulus, W., Rossi, S., Rothwell, J.C., Siebner, H.R., Ugawa, Y., Walsh, V., Ziemann, U., 2015 Jun. Non-invasive electrical and magnetic stimulation of the brain, spinal cord, roots and peripheral nerves: Basic principles and procedures for routine clinical and research application. An updated report from an I.F.C.N. Committee. Clin Neurophysiol. 126 (6), 1071–1107. https://doi.org/10.1016/j.clinph.2015.02.001.