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Review article

The clinical neurophysiology of COVID-19-direct infection, long-term sequelae and para-immunization responses: A literature review

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ABSTRACT

The COVID-19 pandemic resulting from the SARS-CoV-2 virus is in its third year. There is continuously evolving information regarding its pathophysiology and its effects on the nervous system. Clinical neurophysiology techniques are commonly employed to assess for neuroanatomical localization and/or defining the spectrum of neurological illness. There is an evolving body of literature delineating the effects of the SARS-CoV-2 virus on the nervous system as well as para-immunization responses to vaccination against this virus. This review focuses on the use of neurophysiological diagnostic modalities in the evaluation of potential acute and long-term neurological complications in patients that experience direct infection with SARS-CoV-2 and analyzes those reports of para-immunization responses to vaccination against the SARS-CoV-2 virus. The neurophysiological modalities to be discussed include electroencephalography (EEG), evoked potentials (EPs), nerve conduction studies and electromyography (EMG/NCV), autonomic function tests, transcranial magnetic stimulation (TMS) and Transcranial Doppler ultrasound (TCD).

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1. Introduction

More than two years after the first known COVID-19 case was identified, the global spread of the SARS-CoV-2 virus and its emergent variants have resulted in significant morbidity and mortality. While some of the disease burden has been mitigated by the emergence of effective vaccines, the SARS-CoV-2 virus remains a significant public health threat. This manuscript will discuss the neurophysiological evaluation of the neurological manifestations of COVID-19, which is the illness that results from a SARS-CoV-2 viral infection. Specifically, it will review the clinical neurophysiological evaluation of patients infected with SARS-CoV-2 who subsequently develop nervous system complications. It will also discuss reports of neurological illnesses that have been reported as being temporally associated with vaccination against SARS-CoV-2.

The most common reported neurological manifestations of COVID-19 are mild and include fatigue, myalgia, dysosmia, dysgeusia and headache (Misra et al., 2021; Wang et al., 2020). Altered mental status occurs frequently, especially in critically ill patients (Scullen et al., 2020). More serious and less commonly reported complications include cerebrovascular accidents, seizures, meningoencephalitis and the Guillain-Barré syndrome (Misra et al., 2021; Wang et al., 2020; Abdullahi et al., 2020; Favas et al., 2020). Neurological symptoms have also been reported to linger or develop weeks to months after acute infection. These symptoms, which have increasingly been recognized as the sequelae of SARS-CoV-2 include persistent dysosmia and dysgeusia, headache, fatigue, cognitive impairment, dizziness, dysautonomia and peripheral sensory disturbances (Balcom et al., 2021; Grisanti et al., 2022). Several terms have been used to refer to these long-term sequelae of COVID-19 (Stefanou et al., 2022). In this review, we have adopted the term "long COVID."

This review focuses on the use of common neurophysiological diagnostic modalities in the evaluation of neurological signs and symptoms associated with the acute phase of COVID-19 as well as the syndrome designated "long COVID." This manuscript will also review the neurological disorders reported as being temporally associated with vaccination against SARS-CoV-2 given the increasing number of case reports on this subject.

The neurophysiological modalities to be discussed will include electroencephalography (EEG), evoked potentials (EPs), nerve conduction studies and electromyography (EMG/NCV), autonomic function tests, transcranial magnetic stimulation (TMS) and Transcranial Doppler ultrasound (TCD). As previously stated, this manuscript will address the acute phase of COVID-19, the "long COVID" syndrome and the reported association of clinical neurophysiological changes purported to be associated with vaccination against SARS-CoV-2.

Notwithstanding, a recent report by Li et al. found no association between vaccines against SARS-CoV-2 and Bell's palsy, encephalomyelitis, Guillain-Barré syndrome, and transverse myelitis whereas an association with all of these except transverse myelitis was noted with a recent SARS-CoV-2 infection (Li et al., 2022). The peripheral nerve manifestations of COVID-19 have been summarized in an article by Andalib et al. (Andalib et al., 2021).

2. Methods

English language databases were queried using the terms vaccination, COVID-19, SARS-CoV-2, clinical neurophysiology, electroencephalography (EEG), nerve conduction studies and electromyography (EMG/NCV), evoked potentials (EPs), autonomic function tests, transcranial magnetic stimulation (TMS) and Transcranial Doppler ultrasound (TCD). Most of the literature retrieved was that of case reports and small case series.

3. Electroencephalography (EEG)

3.1. Indications for EEG in patients with COVID-19

EEG is commonly utilized to evaluate inpatients with encephalopathy to assess for subclinical seizures to ascertain the underlying cause. Several studies and case series discussing EEG findings in hospitalized patients with COVID-19 since the onset of the pandemic have been reported. Most EEG studies were performed on critically ill patients who were encephalopathic and/or comatose (Pellinen et al., 2020; Danoun et al., 2021). The most common indication for EEG in the context of acute SARS-CoV-2 infection was encephalopathy (61.7–90.4 %), followed by clinical seizures or seizure-like episodes (27.1–34 %) (Antony and Haneef, 2020; Roberto et al., 2020; Kubota et al., 2021). EEG has been also utilized to evaluate patients with cognitive complaints in long COVID and in those patients reporting encephalopathy or seizures after vaccination against SARS-CoV-2.

3.2. EEG in the acute phase of COVID-19

3.2.1. COVID-related encephalopathy

The most commonly encountered EEG abnormalities associated with acute COVID-19 are those consistent with a nonspecific encephalopathy. Most published cases were reported in critically ill, mechanically ventilated patients. Generalized slowing of the EEG background was reported in 91–96.1 % of patients in two large case series (Pellinen et al., 2020; Danoun et al., 2021) and in a meta-analysis of 12 studies (Kubota et al., 2021). Less commonly reported abnormalities, also indicative of a nonspecific encephalopathy, included generalized periodic discharges (GPDs) with triphasic configuration, generalized rhythmic delta activity (GRDA), and discontinuous background and burst-suppression pattern (Pellinen et al., 2020; Danoun et al., 2021; Kubota et al., 2021; Roberto et al., 2020; Antony and Haneef, 2020). Focal slowing has been reported less frequently. In a systematic review of 84 studies with 617 patients, focal slowing was present in 17 % of patients (Antony and Haneef, 2020). Most studies did not provide details regarding the distribution of focal slow activity nor did they correlate it with the presence of chronic or acute findings on brain imag-

ing. However, some studies suggested a frontal predilection for focal slow activity, a concept that is explored in a subsequent section.

3.2.2. Epileptiform abnormalities and seizures

Lin et al. reported the largest published case series on EEG findings in COVID-19 patients, including 197 patients from 9 centers in the United States and Europe. Ictal or interictal epileptiform abnormalities were present in 48.7 % of patients and seizures in 9.6 %, including status epilepticus in 5.6 % (Lin et al., 2021). Almost all patients had other risk factors for symptomatic seizures, including metabolic derangements or history of prior central nervous system disorders (Lin et al., 2021). Hwang et al. reported EEG findings in 192 patients at 4 hospitals in New York, one of the epicenters of the first wave of the pandemic. Epileptiform abnormalities were present in 39.6 %, while seizures occurred in 4.1 % (Hwang et al., 2022). Another large series from New York reported epileptiform discharges in 30 % of 111 patients and seizures in 7 %. Most of these patients had no known history of epilepsy but did have clinical seizures prior to EEG (Pellinen et al., 2020). Comparable findings were reported in a series of 110 patients from Southeast Michigan, with electrographic seizures occurring in 11 % of patients (Danoun et al., 2021). Notably, in all three of these large series, the prevalence of seizures did not seem to be higher than expected in those critically ill patients or those with severe sepsis, regardless of underlying etiology. Previous data from continuous EEG monitoring studies in patients with critical illness or severe sepsis indicate that seizures occur in up to 10–17 % of patients (Oddo et al., 2009; Gilmore et al., 2015), even in the absence of a known primary acute neurological injury (Lin et al., 2021; Oddo et al., 2009). Seizures in the context of COVID-19 were even less frequent in other smaller series, with some reporting no occurrence of seizures on EEG (Galanopoulou et al., 2020; Petrescu et al., 2020; Canham et al., 2020). In a French series of 78 patients, epileptiform discharges were reported in 4 patients and seizures in only one patient (Lambrecq et al., 2021). In a systematic analysis of 86 studies, including 617 patients, epileptiform discharges were reported in 13 %, while status epilepticus was recorded in 1.9 % and 3.6 % respectively (Antony and Haneef, 2020). The variation in these numbers may be reflective of the heterogeneity of the cohorts and practice differences influencing the utilization of long-term EEG monitoring (Lin et al., 2021). In large series, the majority of sporadic interictal epileptiform abnormalities and seizures were described as focal or multifocal (Lin et al., 2021; Pellinen et al., 2020; Hwang et al., 2022; Danoun et al., 2021). Most studies did not provide data regarding the localization of epileptiform discharges. In the series by Hwang et al., interictal epileptiform discharges were almost in the frontal or temporal regions in almost all patients (Hwang et al., 2022).

3.2.3. Are there EEG patterns specific for COVID-19?

One study reported a relatively high occurrence of the alpha coma pattern in a small cohort of patients with severe encephalopathy (Koutroumanidis et al., 2021). This uncommon pattern (Kaplan et al., 1999) was reported in five ICU patients out of 19 who underwent EEG evaluation over a relatively brief period of 6 weeks. The alpha coma pattern is typically associated with hypoxic-ischemic encephalopathy but may also be observed, albeit less frequently, in the context of toxic-metabolic encephalopathies. It has also been described in association with lesions of the pons and midbrain (Kaplan et al., 1999; Loeb and Poggio, 1953; Hauge et al., 1956; Chatrian et al., 1964; Wilkus et al., 1971; Obeso et al., 1980). The authors speculated that the alpha coma pattern may be explained by neurotropic effects of SARS-CoV-2 on the ascending reticular formation (Koutroumanidis et al., 2021; Nuwer, 2021). However, this hypothesis awaits pathological confirmation.

Some studies suggested a frontal preponderance of EEG abnormalities, including slow activity, periodic discharges, and epileptiform discharges (Galanopoulou et al., 2020; Vellieux et al., 2020a; Vespignani et al., 2020). This led to the speculation that these findings may be due to viral neurotropism and the preferential involvement of the frontal lobes via the olfactory bulbs (Antony and Haneef, 2020; Lambrecq et al., 2021; Vellieux et al., 2020b). However, most of these studies were limited by a small sample size and lack of a control group (Pellinen et al., 2020; Danoun et al., 2021). Furthermore, the frontal predominance of some reported EEG abnormalities may not always signify focal frontal pathology. Certain EEG features commonly associated with diffuse encephalopathic processes, such as generalized rhythmic delta activity (GRDA) and generalized periodic discharges (GPDs) with triphasic morphology, often have frontal predominance (Hartshorn and Foreman, 2019).

At the present time, there is no definite evidence to support the presence of a specific EEG pattern associated with COVID-19 encephalopathy (Vellieux et al., 2020b). Further investigation of the prevalence of focal frontal abnormalities and the alpha coma pattern in this population is warranted.

3.3. EEG in long COVID

Some studies suggest a role for EEG in evaluating patients with chronic cognitive complaints following COVID-19. In an Italian study, 49 patients who reported cognitive complaints after resolution of COVID-19 were evaluated using neuropsychological assessment, MRI and QEEG (Cecchetti et al., 2022). Cognitive deficits, (affecting at least one cognitive domain), were present in 53 % of patients at 2 months and 36 % of patients at follow-up within 10 months. QEEG assessed regional activity and connectivity in different bandwidths, using linear lagged connectivity (LLC) and cortical current source densities (CSD). Compared to healthy controls, patients had higher regional current density and connectivity in at the delta band.

A study from Brazil (Andrei Appelt et al., 2022) assessed EEG activity in 53 post-COVID-19 patients and 30 controls at rest and during performance of cognitive tasks including Trail Making Tests (TMT) Parts A and B. In the first group, at 6–12 months after COVID-19, there was a decrease in F3-F7 activity during TMT-B, a reduction in signal complexity at F3-F7 at rest, and a reduction in Fz-F4 activity at rest during TMT-B. However, a notable limitation of this study was the use of a rather abbreviated EEG montage limited to 5 electrodes. Thus, it is difficult to draw definite conclusions from this report.

3.4. EEG in evaluation of post-vaccine complications

There have been multiple reports on the rare occurrence of central nervous system (CNS) complications related to different types of COVID-19 vaccination, including ChAdOx1 nCoV-19, mRNA-1273 and BNT162b2. These included acute encephalopathy (Roberts et al., 2021; Grover et al., 2022; Al-Mashdali et al., 2021; Baldelli et al., 2021) or encephalitis, (Zuhorn et al., 2021; Torrealba-Acosta et al., 2021; Fan et al., 2022; Kobayashi et al., 2022; Zlotnik et al., 2021; Takata et al., 2021) which in some cases were associated with seizures including two cases of new-onset refractory status epilepticus (NORSE), (Fan et al., 2022; Aladdin and Shirah, 2021). There are also several reports of acute disseminated encephalomyelitis (ADEM) or ADEM-like presentations (Vogrig et al., 2021; Cao and Ren, 2022; Ozgen Kenangil et al., 2021; Rinaldi et al., 2021; Kania et al., 2021) and acute necrotizing encephalopathy (Bensaidane et al., 2022; Siriratnam et al., 2022). In almost all of the aforementioned cases, when EEG findings were reported, they consisted of nonspecific generalized slow activity

(Zuhorn et al., 2021; Torrealba-Acosta et al., 2021; Fan et al., 2022; Aladdin and Shirah, 2021; Al-Mashdali et al., 2021; Baldelli et al., 2021; Vogrig et al., 2021; Bensaidane et al., 2022; Siriratnam et al., 2022) or were assessed as normal (Sluyts et al., 2022; Zlotnik et al., 2021; Takata et al., 2021; Grover et al., 2022). Thus, these data indicate that there is no specific EEG pattern that affirms an association of vaccination against SARS-Covid-2 with post-vaccination neurological dysfunction.

3.5. Summary

In conclusion, the most common EEG findings in critically ill patients with COVID-19 are those consistent with a nonspecific encephalopathy. Interictal epileptiform discharges and seizures may be observed in a significant percentage of patients including episodes of status epilepticus. However, based on the available evidence, seizures do not seem to be more prevalent in critically ill patients with COVID-19 than those with sepsis of other etiologies. EEG is clinically useful in the evaluation of seizures and encephalopathy of various etiologies, including COVID-19. Moreover, EEG may also be useful in the evaluation of cognitive complaints in long COVID. Nonetheless, there is no evidence of specific EEG findings in any of these groups.

4. Evoked potentials (EPs)

4.1. Indications for EPs in patients with COVID-19

Evoked potential studies are generally employed to evaluate large, myelinated pathways originating peripherally and traversing the central nervous system. A literature review did not identify specific signatures unique to COVID-19. Nonetheless, visual, auditory, somatosensory, and olfactory evoked potentials have been used to investigate symptoms related to COVID-19. Each of these studies are discussed in sequence.

4.2. Visual evoked potentials (VEPs)

Visual evoked potentials (VEP) assess the visual pathways from the cornea to the occipital cortex, although they are most employed to assess for lesions of the optic tract anterior to the chiasm. Koskderelioglu et al. assessed 76 patients who recovered from COVID-19 and compared them to 44 normal controls noting no significant differences between these two groups although 12 patients with COVID-19 had prolonged P100 latencies representing subclinical anterior visual pathway dysfunction (Koskderelioglu et al., 2022). Notably, none of these patients manifested electrophysiological evidence of a peripheral neuropathy. Nagaratnam et al. reported a case of bilateral optic neuritis following a ChAdOx1 COVID-19 vaccination (Nagaratnam et al., 2022). Rodrigo-Armenteros et al. reported a case of 62-year-old male, with left eye amblyopia since childhood who presented with asymptomatic left optic neuropathy and a prolonged left P100 latency after a COVID-19 infection (Rodrigo-Armenteros et al., 2022). A small case series from Poland of 4 women with an average 6-year history of relapsing remitting multiple sclerosis reported that, "Visual evoked potentials (VEP) in all cases showed prolonged latency of P-100 waves," although no further clarification was provided (Adamczyk-Sowa et al., 2021). This finding is of uncertain clinical significance as the prolonged P-100 latencies may have been present from the antecedent diagnosis of multiple sclerosis. It is noteworthy that none of these patients manifested brainstem auditory evoked potential abnormalities, which provides electrophysiological evidence against widespread central nervous system (CNS) demyelination. Moreover, CNS demyelination associated with COVID-19 may manifest unremarkable VEPs (Metya et al., 2021). Although there has been some pathological evidence of SARS-CoV-2 virus neurotropism, it is unclear if the clinical manifestations are due to an autoimmune response to the virus or a direct result of neuroinvasion (Costello and Dalakas, 2020). Nonetheless, VEPs do not appear to be able to distinguish myelin dysfunction due to COVID-19 or para-vaccination demyelination from other causes of central nervous system demyelinating disease.

4.3. Brainstem auditory evoked responses (BAERs)

Dror et al. compared BAERs in 8 asymptomatic COVID-19 positive patients who recovered from their illnesses to age matched controls noting no differences in transitory evoked otoacoustic emission, distortion product otoacoustic emissions or BAERs (Dror et al., 2021). Vecchio et al performed BAERs in 10 who were being evaluated for difficulty weaning off mechanical ventilation. Four patients were reported to have an increased interpeak III-V wave latency, suggesting lesions between the caudal pons and midbrain- a finding that may lend support to the notion of brainstem involvement in severe COVID-19 (Vecchio et al., 2022). Niguet et al. reported on 17 BAERs that were performed in critically ill COVID-19 patients because of a persistent lack of clinical and/or EEG reactivity (Niguet et al., 2021). They reported that "…2 were uninterpretable because of agitation, 6 were normal, and 9 (52,9%) showed peripheric [sic] disorganization of BAEP (decreased amplitude with difficulties to identify waves I, III, V; since wave I whose generator is peripheral was abnormal, VIIIth nerve was involved), which was unilateral in 4 cases. None showed specific brainstem dysfunction. These results were in favor of a preservation of central somatosensory and auditory systems." Netravathi et al. examined 29 patients with central nervous system (CNS) demyelination following immunization against COVID-19 with ChAdOx1-S (n = 27) and BBV152 vaccinations (n = 2), 7 of whom underwent BAERs that were unremarkable (Netravathi et al., 2022). Overall, BAERs appear to be a relatively insensitive test for the evaluation of suspected COVID-19 infection or para-immunization demyelination.

4.4. Somatosensory evoked potentials (SSEPs)

The most common SSEPs are those of the tibial and median nerves. Tibial SSEPs have an advantage in that they incorporate the entirety of the spinal cord's dorsal columns but they are more likely to be affected by peripheral neuropathy. Thus, most patients admitted to the ICU undergo median SSEPs, which are less likely to be affected by peripheral neuropathies such as critical illness neuropathy. Of the 17 patients who underwent median SSEPs as reported by Niguet et al., "2 were uninterpretable because of agitation, 2 showed peripheral abnormalities of N9 (generator: brachial plexus), either in latency or amplitude, 1 showed no response (corresponding to the patient with Guillain-Barré syndrome) and 12 were considered as normal with N20 latency within the normal ranges" (Niguet et al., 2021). It should also be recalled that SSEPs assess the peripheral nervous system as well as noted in an 82-year-old woman who developed, "pure sensitive [sic] chronic inflammatory axonal polyneuropathy (CIAP) in a close temporal relationship with the administration of the BNT162b2 (Pfizer®) vaccine" (Luca et al., 2022). These authors reported that somatosensory evoked potentials (SSEPs), presumably tibial SSEPs, were not recordable but that a spine MRI demonstrated nerve root enhancement from C3 to Th2 and diffuse enhancement of cauda equina nerve roots. In aggregate, SSEPs may detect pathology within the large fiber sensory pathways but there does not appear to be a signature unique to COVID-19 or to temporally associated para-vaccination demyelination.

5. Electromyography and nerve conduction studies (EMG/NCV)

5.1. Indications for EMG/NCV in patients with COVID-19

Guidon and Amato reported that there is no current evidence of direct viral invasion with inflammation or degeneration of motor neurons and peripheral nerves as seen in some viral infection (Guidon and Amato, 2020). Therefore, the indications for EMG/NCVs would be for peripheral nervous system (PNS) disorders suspected to be related to COVID-19 or associated with a recent vaccination against SARS-CoV-2. These entities would include neuropathies, predominantly autoimmune neuropathies, Bell's palsy as a presumed autoimmune mononeuropathy, neuromuscular junction disorders, and myopathies.

5.2. EMG/NCV in the acute phase of COVID-19

5.2.1. Guillain-Barré syndrome (GBS)

Caress et al. reviewed available EMG data in 32/37 cases of GBS associated with COVID-19 noting that the AIDP variant was identified in 24 cases, (18 were classified as demyelinating), 5 cases of acute motor sensory axonal neuropathy (AMSAN), 5 cases of the Miller Fisher variant, 1 case of acute motor axonal neuropathy (AMAN) and 2 that were not specifically classified (Caress et al., 2020). A European experience of 42 cases of Guillain-Barré syndrome (GBS) reported that patients (80.5 %) had electrodiagnostic features of acute inflammatory demyelinating polyradiculoneuropathy (AIDP) (Uncini et al., 2020). They also noted that five patients (13.9 %) were reported to have the acute motor and sensory axonal subtype although one of these cases did have some demyelinating features. When parsing isolated case reports, there does not seem to be a distinction in the distribution of "axonal" versus "demyelinating" variants between SARS-CoV-2 and other viruses known to be associated with GBS. Interestingly, in a comparison of 48 cases of AIDP associated with COVID-19 with 49 control AIDP cases, COVID-19 patients were more likely to have increased distal compound muscle action potential (dCMAP) latencies and F waves were more often absent (Uncini et al., 2021). The authors attributed the former finding to additional muscle fiber conduction slowing, possibly due to a hyperinflammatory state, and the latter to decreased α-motor neuron excitability due to immobilization in the ICU.

Thus, EMG/NCV are useful in the diagnosis of the GBS syndrome but there is no specific electrophysiological signature specific to COVID-19 or the sequelae of vaccination against SARS-COV-2. Even when GBS is identified, COVID-19 does not appear to have a predilection for AIDP over the axonal variants or their subtypes.

5.2.2. Bell's palsy

Gupta et al. reviewed 20 published cases of COVID-19 positive patients in which Bell's palsy was the only major neurological manifestation presenting within several days of the infection (Gupta et al., 2021). These authors did not include clinical neurophysiological assessments of the facial nerve in their manuscript. The relationship of Bell's palsy to vaccination against SARS-CoV-2 remains controversial with two studies noting that there was no statistically significant association (Shemer et al., 2021; Tamaki et al., 2021). Shemer et al. found no association between the BNT162b2 (Pfizer-BioNTech) COVID-19 vaccine and Bell's palsy, nor did they find an increased incidence of Bell's palsy compared to the historical incidence of Bell's palsy prior to the current pandemic. These reports are clinically based and did not use electrodiagnostic assessments as an inclusion criterion for a case of Bell's palsy. While electrodiagnostic assessments of infranuclear facial neuropathy are useful for prognostication of clinical outcome in Bell's palsy, the literature does not establish specific electrodiagnostic parameters that distinguish Bell's palsy resulting from SARS-CoV-2 versus other etiologies (Grosheva et al., 2008).

5.2.3. Myasthenia gravis

There is a case report of a 21-year-old woman with a family history of autoimmune diseases who developed myasthenia gravis [MG] after an infection with the SARS-CoV-2 virus who did not undergo electrodiagnostic testing (Huber et al., 2020). There are other reports of COVID-19 exacerbating symptoms in persons previously diagnosed with myasthenia gravis (Anand et al., 2020; Saied et al., 2021). This is consistent with numerous prior reports of myasthenic crises or exacerbations precipitated by an augmentation of the immune response, which often occurs in the context of a newly acquired infection. Neither of these reports used clinical neurophysiology as an inclusion criterion as a case definition. Similarly, there is an isolated case report of MG that developed after vaccination against SARS-CoV-2 although the authors clearly state that the literature does not support an association (Lee et al., 2022). These authors reported that a repetitive nerve stimulation test revealed a significant decrement response in the right orbicularis oculi but did not state that there was anything unique about the electrodiagnostic findings. As with Bell's palsy, there do not appear to be any unique electrodiagnostic features that are pathognomonic to MG associated with SARS-CoV-2 much less a specific relationship between vaccination against this virus and the subsequent development of MG.

5.2.4. Myopathy/critical illness neuropathy/critical illness myopathy

These complications of SARS-CoV-2 have been summarized and include myalgias, which are most common, inflammatory myopathies and critical illness syndromes such as critical illness neuropathy/neuropathy (Andalib et al., 2021; Orsucci et al., 2020). Neither of these publications reported on electrodiagnostic findings pathognomonic to SARS-CoV-2.

Since the first report of critical illness myopathy (CIM) associated with severe COVID-19 (Tankisi et al., 2020), there have been several additional reports suggesting that CIM as well as critical illness neuropathy (CIN) are common in critically ill COVID-19 patients. Hameed et al. reported on a case series of 18 mechanically ventilated patients infected with COVID-19 of whom 82 % were diagnosed with myopathy based on low amplitude brief duration motor unit action potentials (Hameed et al., 2021). Five of these patients had a concurrent axonal neuropathy. In a Swedish observational study of 111 critically ill patients, 11 developed CIM/CIN. Unsurprisingly, these patients had severe illness and prolonged ICU stays. In the same study, CIN was more frequent in COVID-19 patients than in a non-COVID cohort (Frithiof et al., 2021). One study evaluated 31 patients on mechanical ventilation underwent periodic muscle excitability measurements on days 1, 2, 5 and 10 post-intubation, in addition to EMG/NCV on day 10. Seventeen patients (55 %) developed CIM. Muscle excitability measurements on day 10 distinguished between patients who developed CIM and those who did not, suggesting that muscle excitability measures may be helpful in establishing the diagnosis of CIM (Rodriguez et al., 2022). Interestingly, in a study of 12 non-ventilated subjects with COVID-19, subclinical myopathy was reported to be present in half of these patients (Villa et al., 2021). Versace et al. described two critically-ill COVID-19 patients with typical neurophysiologic findings of myopathy, and observed the presence of increased distal CMAP duration that did not change between distal and proximal stimulation, despite normal distal motor latencies and conduction velocities. The authors hypothesized that this finding could be explained by decreased muscle membrane excitability and slowed muscle fiber conduction within

the context of a COVID-associated hyperinflammatory state (Versace et al., 2021b).

5.3. EMG/NCV in long COVID

EMG/NCV have been used to evaluate patients with persistent fatigue, myalgias, sensory disturbances and dysautonomia persisting after acute COVID.

In one study (Agergaard et al., 2021), 20 patients with sensory symptoms after acute COVID-19 underwent NCV and quantitative EMG (qEMG) to assess for neuropathy. Although no electrophysiological evidence of neuropathy was found, 11 patients (55 %) were noted to have myopathic changes in one or more muscles on qEMG, at an average of 210 days after COVID-19. All these patients endorsed having fatigue and 73 % reported myalgias. These authors hypothesized that myopathy may be a cause of fatigue in long COVID (Agergaard et al., 2021). This hypothesis was further supported by another study (Hejbol et al., 2022) which reported qEMG and muscle biopsy findings in 16 patients reporting fatigue, myalgia or weakness persisting for up to 14 months after COVID-19. Electromyographic findings consistent with myopathy, (i.e., low amplitude, brief duration motor unit action potentials), were noted in 75 % of those evaluated whereas histopathological changes were present in all patients, including muscle fiber atrophy, mitochondrial changes, inflammation, and capillary injury (Hejbol et al., 2022).

While several studies failed to show evidence of large-fiber neuropathy in patients with chronic sensory complaints in long COVID (Abrams et al., 2022; Agergaard et al., 2021), there is evidence of small fiber involvement and dysautonomia in some patients, based on skin biopsies and autonomic function tests. This is discussed in more detail in a subsequent section.

5.4. EMG/NCV in evaluation of post-vaccine complications

With respect to vaccination against SARS-CoV-2, there is an isolated case report of dermatomyositis, (Camargo Coronel et al., 2022) and another of rhabdomyolysis, (Cirillo et al., 2022). Neither of these reports stated that the medical literature affirmed an association between vaccination against SARS-CoV-2 and neither of these reports specified electrodiagnostic findings unique to vaccination against SARS-CoV-2.

6. Transcranial magnetic stimulation (TMS)

Two studies reported on the use of TMS of the primary motor cortex (M1) in evaluating patients with long COVID and fatigue and/or cognitive complaints (Versace et al., 2021a, Ortelli et al., 2021). The first study included 12 patients who underwent neuropsychological evaluation and TMS. In comparison to 10 healthy controls, "long-COVID" patients demonstrated disruptions of both short and long interval intracortical inhibition (SICI and LICI), which reflect GABAergic activity. There was also a slight reduction of short-latency afferent inhibition (SAI), which reflects cholinergic activity. The findings were interpreted as suggestive of reduced intracortical GABAergic activity and, to a lesser extent, cholinergic activity which may underlie post-COVID cognitive deficits and fatigue (Versace et al., 2021a). Ortelli et al. evaluated 67 post-COVID patients that were compared to 22 healthy controls. The authors interpreted their findings as being consistent with reduced M1 cortical excitability in post-COVID patients, evidenced by higher resting motor thresholds (RMTs), lower motor evoked potential (MEP) amplitudes and longer cortical silent periods. This study also reported impairments of SICI, LICI, and SAI, thus lending further support to the notion of altered GABAergic and cholinergic neurotransmission (Ortelli et al., 2021). In a related follow-up study, these authors opined that the impairment of executive function and attention and changes in M1 neurophysiology indicated a dysfunction of frontal lobe networks in long COVID (Ortelli et al., 2022).

7. Autonomic function tests

Some studies have evaluated long-COVID patients with peripheral sensory or autonomic symptoms, which often overlap, and reported evidence of small-fiber neuropathy (SFN) and dysautonomia. In a study by Abrams et al, skin biopsies were performed in 13 patients with new-onset paresthesias (including 7 with autonomic symptoms) within 2 months of acute COVID-19 symptoms which they designated as "mild" in all but one patient. Evidence of SFN was found in 6 patients, two of whom also manifested evidence autonomic dysfunction on autonomic function testing (Abrams et al., 2022). Another study found a high prevalence of SFN and dysautonomia (89 % and 100 % respectively) in a cohort of 9 long-COVID patients manifesting as fatigue, "brain fog" and orthostatic intolerance (Novak et al., 2022).

Oaklander et al. reported on 17 patients with long COVID and neuropathic symptoms. Evaluation included skin biopsies (16 patients), EMG/NCV (12) and autonomic function tests (8). Findings confirming neuropathy on at least one test were found in 59 %. Most patients were diagnosed with small fiber neuropathy and one patient had a multifocal demyelinating neuropathy, which developed 3 weeks after a mild case of COVID-19 (Oaklander et al., 2022).

One study focused on the findings of autonomic function tests in 27 patients with long COVID and symptoms suggestive of dysautonomia (Shouman et al., 2021). The testing yielded abnormal results in 63 % of patients. These included abnormalities in the quantitative sudomotor axon reflex (36 %), cardiovagal testing (27 %), and cardiovascular adrenergic function (7 %). The criteria for postural orthostatic tachycardia syndrome were met in 22 %. Nonetheless, most patients who reported subjective orthostatic hypotension manifested no evidence of postural tachycardia or hypotension.

8. Transcranial Doppler ultrasound (TCD)

Several factors have been implicated in the causation of stroke in the context of COVID-19, including vasculitis, hypercoagulable state, and cardiomyopathy. It has been demonstrated that endothelialitis may be a direct result of viral involvement and/or the ensuing inflammatory response (Spence et al., 2020). TCD is a noninvasive technique that allows for quick evaluation of the hemodynamic status of cerebral circulation and the detection and monitoring of emboli (Tsivgoulis et al., 2009). Therefore, TCD has been used in the clinical evaluation of COVID-19 patients and offered insights into the pathophysiology of neurological sequelae of this disease.

In a small series of 6 patients, TCD identified microemboli in 3 patients who experienced neurological complications in the acute phase of COVID-19- two with ischemic stroke and one with persistent encephalopathy (Batra et al., 2021). Another study of 26 critically ill patients with confirmed or suspected COVID-19 could not confirm the presence of microembolic signals, but noted the presence of relatively low cerebral blood flow velocities given low arterial oxygen content and low hematocrit and absence of decreased cardiac output (Ziai et al., 2021). Conversely, another study found higher basal blood flow velocity in patients with COVID-19 than healthy controls, along with a decrease in vasomo-

tor reactivity (Sonkaya et al., 2021). The clinical significance of these findings remains to be determined.

Abdo-Cuza et al used TCD to evaluate baseline and post-apnea cerebral hemodynamic patterns in 25 patients who had recovered from COVID-19 as compared to 26 controls (Abdo-Cuza et al., 2022). Baseline cerebral hemodynamics were similar but patients with previous COVID-19 had lower hemodynamic reserve and breath-holding index changes that could be attributable to endothelial injury. Notably, these changes did not appear to be related to the severity of the disease or the presence of neurological symptoms.

While larger studies are not yet available, these data suggest that TCD may be helpful in the evaluation and follow-up of patients with COVID-19.

9. Conclusion

SARS-CoV-2 has the potential to induce a plethora of central and peripheral nervous system diseases both acutely and chronically. Most of the literature attributes manifestations of COVID-19 to a parainfectious response rather than a direct invasion of the nervous system. Vaccination against SARS-CoV-2 has the potential to induce a parainfectious response although Li et al. found no statistically significant association between vaccination against SARS-CoV-2 and Bell's palsy, encephalomyelitis, Guillain-Barré syndrome, and transverse myelitis whereas an association with all of these except transverse myelitis was noted with a recent SARS-CoV-2 infection (Li et al., 2022). Nonetheless, there is no unique or pathognomonic electrophysiological signature that distinguishes SARS-CoV-2 from other causes of nervous system disorders. Thus, clinical neurophysiology should be used as an investigative tool to determine which portions of the nervous system are affected by SARS-CoV-2 or its parainfectious response. Disorders suspected to be associated with a recent vaccination against SARS-CoV-2 should be investigated in a similar manner. Neurophysiologic modalities may also have a role in the evaluation of ‘‘long COVID” as they may provide objective validation of the patient's reported symptoms. Overall, clinical neurophysiology studies are useful in assessing symptomatology related to COVID-19 or vaccination against the SARS-CoV-2 virus but cannot affirm a causative association. While further studies are warranted, there appears to be an organic basis to the long COVID syndrome as assessed by clinical neurophysiology. Notwithstanding, there is no specific electrodiagnostic signature that is pathognomonic for SARS-CoV-2 infection, a vaccine associated response or one that affirms ‘‘long COVID.” Therefore, clinical neurophysiology should not be used to affirm an association between COVID-19 or a vaccine against SARS-CoV-2 with a specific clinical diagnosis. Moreover, clinical neurophysiological abnormalities observed in ‘‘long COVID” are not invariably present and do not necessarily imply causation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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