

Normative Values of Whole Plantar Nerve Conduction Study in Healthy Individuals

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ABSTRACT

Introduction: Whole plantar nerve conduction study (WPNCS) is the method, in which medial and lateral plantar nerves are stimulated simultaneously with appropriate surface electrodes, and compound nerve action potentials (CNAPs) are recorded with bipolar surface electrodes proximal to the flexor retinaculum. Our aim was to determine normative values of nerve conduction study results.

Methods: The study included 90 healthy volunteers of both sexes aged between 18 and 60 years. To record CNAPs, a bipolar disc electrode was placed in a proximal position near the flexor retinaculum on the ankle. Medial and lateral plantar nerves were stimulated simultaneously from the anterior transverse arch of the sole. **Results:** The mean CNAP amplitude was 22.82 ± 8.16 (95% confidence interval [CI]: 21.62–24.02) μV , with a lower limit of 10.1 and a 5th percentile value of 11.69. The mean CNAP maximum nerve conduction velocity (NCV) was 58.33 ± 5.47 (95% CI: 57.52–59.13) m/s, with a lower limit of 45.2 and a 5th percentile value of 50.0. The mean CNAP negative peak NCV was 42.95 ± 3.67 (95% CI: 42.41–43.49) m/s, with a lower limit of 34.6 and a 5th percentile value of 37.0. **Conclusion:** This study represents an electrophysiology investigation to determine normative values in a large number of volunteers with a slight technical modification after the description of the WPNCS method in 2015. It is anticipated that these limit values will be employed in the future for the diagnosis of peripheral nervous system pathologies.

KEYWORDS: Lateral plantar nerve, medial plantar nerve, nerve conduction study, tarsal tunnel syndrome, whole plantar nerve conduction study

INTRODUCTION

The medial and lateral plantar nerves are the distal branches that arise from the posterior tibial nerve (L4-S3) at the level of the tarsal tunnel. The medial plantar nerve is a sensory and motor (mixed) nerve of the medial plantar aspect of the foot, whereas the lateral plantar nerve is a mixed nerve of the lateral plantar aspect of the foot.^[1] The abductor hallucis, flexor hallucis brevis, flexor digitorum brevis, and the first lumbrical muscle are all innervated by the medial plantar nerve, in addition to its sensory role. The lateral plantar nerve is the motor nerve responsible for the remaining intrinsic foot muscles.^[2] Tarsal tunnel syndrome (TTS) is an entrapment neuropathy of the posterior tibial nerve.^[3] The diagnostic value of various electrophysiologic techniques for the sensory functions of the medial and lateral

plantar nerves has been well documented. The nerve conduction studies by Saeed *et al.* and Oh *et al.* are the most trustworthy research to date. In the former study, bipolar surface electrodes were applied to stimulate the medial and lateral plantar nerves independently, with the results being recorded orthodromically from the sole of the foot in the vicinity of the flexor retinaculum.^[4] The latter stimulated the first and fifth fingers separately with ring electrodes and recorded using near-nerve needle electrodes over the flexor retinaculum.^[5]

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Nevertheless, in these studies, it is not always straightforward to obtain and record sensory nerve action potentials (SNAPs).^[6] Consequently, novel techniques in nerve conduction studies have recently emerged. One such method is the stimulation of the medial plantar nerve using a ring electrode on the first finger and the subsequent recording of the SNAP using a surface electrode on the sole of the foot.^[7] The second method involves the recording of the medial plantar digital nerve SNAP in an antidromic manner from the first finger.^[8]

Another recently developed method is “whole plantar nerve conduction study” (WPNCs), which was initially described by Hemmi *et al.* in 2015. In this method, the medial and lateral nerves are stimulated simultaneously with appropriate surface electrodes, and compound nerve action potentials (CNAPs) are recorded using bipolar surface electrodes proximal to the flexor retinaculum.^[9] This method facilitates the acquisition of CNAPs by simultaneously stimulating the medial and lateral plantar nerves, and it is a highly practical and expeditious study. However, because insufficient research has been performed on healthy individuals, it is currently impossible to draw firm conclusions regarding the mean and lower limit values of normal electrophysiologic values in terms of amplitude and nerve conduction velocities (NCVs).

Therefore, the objective of this study was to perform WPNCs on a large healthy population and determine the mean and lower limit values of the resulting CNAPs, with a particular focus on NCV and amplitude. It is anticipated that these results will provide guidance for an earlier electrophysiologic diagnosis of TTS and distal polyneuropathies.

METHODS

Subjects

The study included 90 healthy volunteers of both sexes aged between 18 and 60 years. Before the commencement of the study, written informed consent was obtained from all participants. The study was conducted in accordance with the latest version of the Declaration of Helsinki and received approval from the ethics committee of Bilkent City Hospital (E2-24-6678). Individuals with polyneuropathy of any etiology (e.g., diabetic, inflammatory, and hereditary), those who had undergone previous lumbar laminectomy surgery, those with peripheral nerve damage in the lower extremities, including those who have clinical, radiologic, or electrophysiologic evidence of TTS, medial plantar neuropathy, or lateral plantar neuropathy proved by Saeed’s method,^[4] patients with Type 1 and 2 diabetes

mellitus regardless of whether diabetic polyneuropathy proven by electrophysiologic techniques was present, patients with acute and chronic renal or hepatic failure, pregnant and breastfeeding women, alcohol and substance abusers according to the Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition criteria, those who have experienced pain, numbness, paraesthesia or discomfort in their feet, and patients who sustained blunt or penetrating trauma to the lower extremities in the last 6 months were excluded from the study.

Electrophysiology

The study was conducted in April and May 2024 in the electrophysiology laboratory of our clinic. The temperature of the electrophysiology laboratory was maintained at 23°C–24°C. The Nihon Kohden MEB-9400A EMG/EP system (Tokyo, Japan) was used for nerve conduction studies. Before WPNCs measurements, volunteers were asked to lie comfortably in the supine position. Both feet were cleaned with alcohol and maintained at a temperature above 32°C. To record CNAPs, the active bipolar disc electrode was placed in a proximal position near the flexor retinaculum on the ankle, and the reference electrode was placed 3 cm away from it. Natus disposable ring electrodes (Wisconsin, USA) were used as strip electrodes to stimulate both the medial and lateral plantar nerves simultaneously. The active electrode was positioned near the anterior transverse arch on the sole of the foot, and the passive electrode was situated 2 cm distal to the active electrode. The ground electrode was situated between the stimulator and the recording electrodes. Instead of a fixed distance preference, to prevent individual differences in foot sizes from affecting the results, the sum of two separate subdistances was used to measure the distance between the recording electrode and the stimulator electrode. The first subdistance (x) is the section between the active recording electrode and the distal edge of the flexor retinaculum, where the medial and lateral plantar nerves still run together. The second one (y) is the subdistance from the point where the medial and lateral plantar nerves separate from each other to the stimulator electrode [Figure 1]. The low-pass filter was set to a frequency of 20 Hz, and the high-pass filter was set to 2000 Hz. Volunteers were subjected to orthodromically supramaximal stimulation from the stimulation electrodes and analyzed 10 times. The peak latencies, onset latencies, baseline-to-negative-peak amplitudes, and NCVs, which were calculated according to the onset latency (maximum NCVs), and the negative peak latency (negative-peak NCVs) of the CNAPs, were obtained in accordance with the above methods [Figure 2]. The procedures were applied to both lower extremities.

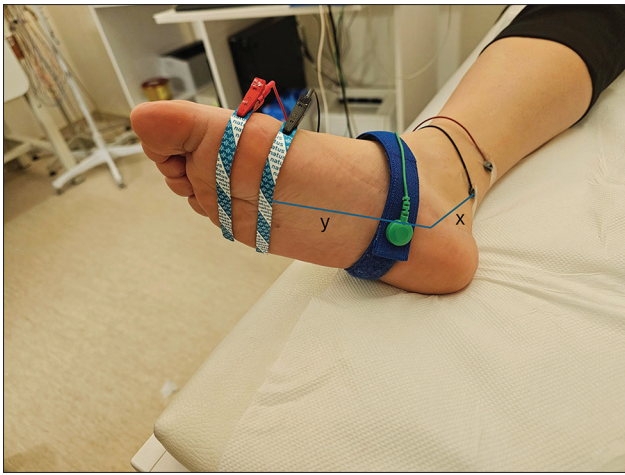


Figure 1: X and Y subdistances were summed to determine the distance used in calculating the nerve conduction velocities

Statistical analysis

The statistical analysis was conducted using the SPSS statistical software package (Version 22, SPSS Inc., Chicago, IL, USA) and the open-source software R Studio (IDE version: 2023.06.2). The data were visualized using the open-source “ggplot2” library available in R Studio. Categorical data were presented as frequencies (*n*) and percentages (%). The assumption of normality for numerical data was evaluated using the Kolmogorov–Smirnov test and graphical approaches (histograms and Q-Q plots). Descriptive statistics for numerical data are reported as mean $\pm$ standard deviation because the data met the assumption of normal distribution. In the absence of outliers, the lower limit was taken to be the minimum value. In the presence of outliers, the lower limit was calculated using the formula: lower limit = $Q1 - 1.5 * (Q3 - Q1)$, where Q1 represents the first quartile, Q3 represents the third quartile, and $Q3 - Q1$ represents the interquartile range. Given that no outliers were identified in the parameters obtained in the study, the lower limits of the CNAP measurements were accepted as the minimum values. Quantile regression was used to derive estimates of the lower (e.g., 5th) percentiles of the CNAP measurements. Quantile regression is a semi-parametric regression analysis technique that relies more on the ranking of actual data and allows for the estimation of percentile values of a response variable.^[10]

RESULTS

The nerve conduction data obtained from a total of 180 feet of 90 individuals were statistically analyzed in the study. Of the participants, 42.2% (*n* = 38) were male and 57.8% (*n* = 52) were female. The mean age of the participants was 37.61 ± 9.77 (range: 19–59) years.

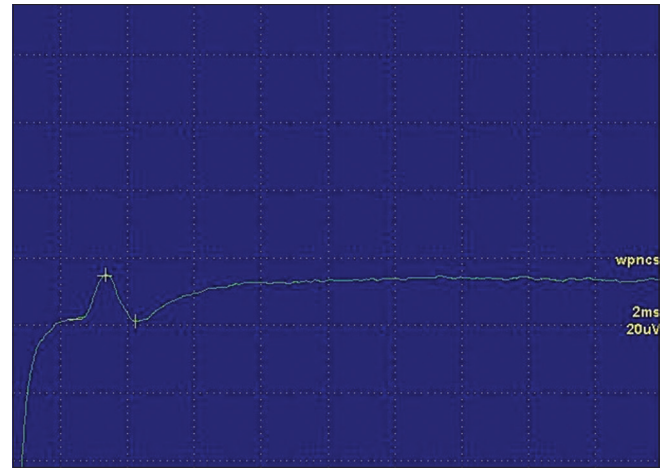


Figure 2: Compound nerve action potential obtained using whole plantar nerve conduction study in a 34-year-old female healthy subject

Statistical findings for CNAP onset latency, negative peak latency, baseline-to-peak amplitude, maximum NCV, and negative peak NCV are presented in Table 1.

The mean CNAP onset latency was 2.45 ± 0.35 (95% confidence interval [CI]: 2.4–2.5) ms, with a lower limit of 1.58 and a 5th percentile value of 1.96. The mean CNAP negative peak latency was 3.31 ± 0.42 (95% CI: 3.24–3.37) ms, with a lower limit of 2.32 and a 5th percentile value of 2.72. Boxplot with jitter showing the distribution of CNAP onset latency and negative peak latency is presented in Figure 3a and b, respectively.

The mean CNAP amplitude was 22.82 ± 8.16 (95% CI: 21.62–24.02) μ V, with a lower limit of 10.1 and a 5th percentile value of 11.69. Boxplot with jitter showing the distribution of CNAP amplitude is presented in Figure 4.

The mean CNAP maximum NCV was 58.33 ± 5.47 (95% CI: 57.52–59.13) m/s, with a lower limit of 45.2 and a 5th percentile value of 50.0. The mean CNAP negative peak NCV was 42.95 ± 3.67 (95% CI: 42.41–43.49) m/s, with a lower limit of 34.6 and a 5th percentile value of 37.0. Boxplot with jitter showing the distribution of CNAP maximum velocity and negative peak velocity is presented in Figure 5a and b, respectively.

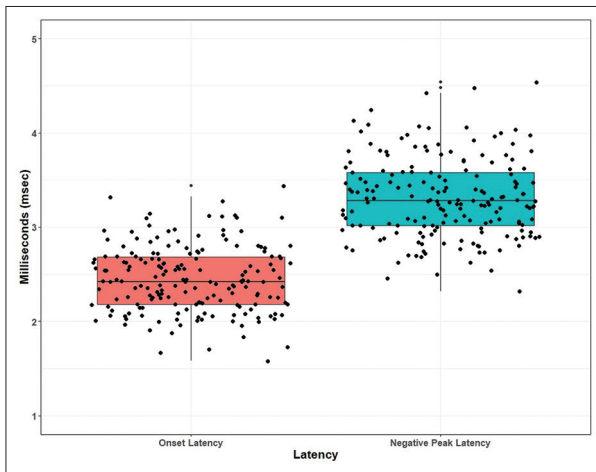
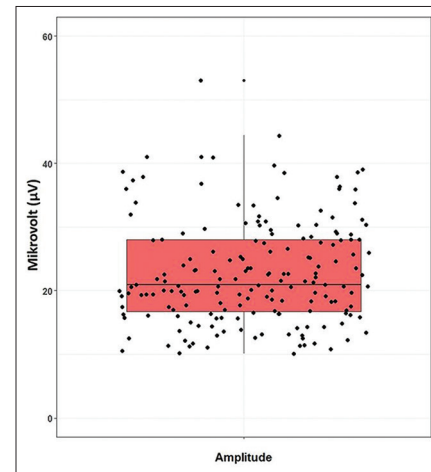
DISCUSSION

In this study, WPNCs parameters of a large group of volunteers were measured and the mean and 5th percentile lower limit values of CNAPs in terms of NCV and amplitude were calculated. In our study, the maximum NCV lower limit of CNAPs was 50.0 m/s, the negative peak NCV lower limit was 37.0 m/s, and the amplitude lower limit was 11.69 μ V.

Table 1: Statistical findings for compound nerve action potential measurements: Onset latency, negative peak latency, amplitude, maximum velocity, and negative peak velocity

	Mean±SD	95% CI for mean	Lower limit	Lower (5 th) percentiles
Onset latency (ms)	2.45±0.35	2.4–2.5	1.58	1.96
Negative peak latency (ms)	3.31±0.42	3.24–3.37	2.32	2.72
Amplitude (μV)	22.82±8.16	21.62–24.02	10.1	11.69
Maximum velocity (m/s)	58.33±5.47	57.52–59.13	45.2	50
Negative peak velocity (m/s)	42.95±3.67	42.41–43.49	34.6	37

SD: Standard deviation, CI: Confidence interval

**Figure 3:** Boxplot with jitter showing the distribution of compound nerve action potential onset latency and negative peak latency**Figure 4:** Boxplot with jitter showing the distribution of compound nerve action potential amplitude

In their initial description of WPNCS, Hemmi *et al.* used a fixed distance of 14 cm between the stimulator and recording electrodes.^[9] In our approach, we positioned the active stimulator electrode in a proximal location to the anterior transverse arch. The rationale behind this choice was to prevent stimulation of a different anatomical point on the nerves in each volunteer by disposable stripe electrodes.

Despite the abovementioned minor methodological differences in electrophysiology and the fact that they used a different percentile when calculating the lower limits, the lower limits for maximum NCV and negative peak NCV were comparable between us (maximum NCV: 50.0 m/s and 48.0 m/s, respectively, negative peak NCV 37.0 m/s and 37.5 m/s, respectively). However, although we identified a lower limit of 11.69 μV for the amplitude, the value provided by the other group was 7.1 μV. This discrepancy may be attributed to our selection of the anterior transverse arch as a landmark; the possibility that stimulation of the plantar nerves is easier in this anatomical region may have caused this difference. Conversely, it does not appear logical to compare the onset and negative peak latencies between the two studies, given that they used a fixed distance, and we used a fixed anatomical landmark.

Galiero *et al.* used WPNCS in the electrophysiological diagnosis of diabetic neuropathy.^[11] In this study, various distances were employed in the electrophysiological studies rather than anatomical landmarks or fixed distances, and only maximum NCV and baseline-to-peak amplitude lower limits were measured. Their findings were interpreted statistically, but a percentile calculation was not made and the maximum NCV lower limit of the control group was found as 39.2 m/s and the baseline-to-peak amplitude lower limit was 6.8 μV (in our study, these values were 45.2 m/s and 10.1 μV, respectively). These values are smaller than ours. The reason for this may be that Galiero *et al.* included people with a median age of 65 years in the control group, who were already diagnosed as having diabetes mellitus, but polyneuropathy was only considered through standard examinations and questionnaires. In other words, there is no healthy control group without diabetes mellitus in this study. Therefore, it is not appropriate to compare the findings of our study with the findings above, both in terms of volunteer selection and due to methodological differences. In another recent study, patients with type 2 diabetes were compared with healthy controls, and the mean CNAP value in healthy volunteers was found as 5.1 μV.^[12] This result is lower than the value we found. Although the number of plantar nerves examined in

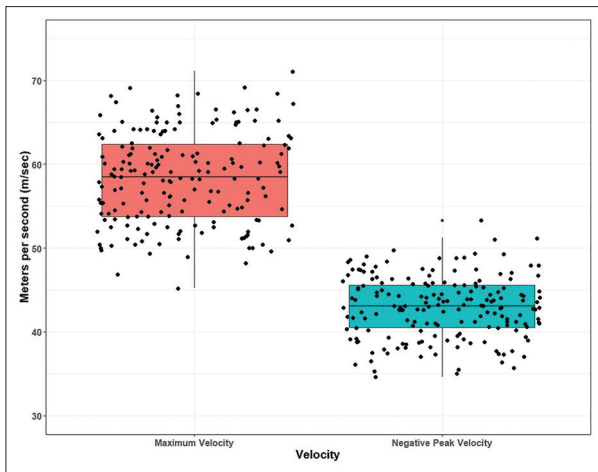


Figure 5: Boxplot with jitter showing the distribution of compound nerve action potential maximum velocity and negative peak velocity

our study was considerably higher than in that study, we think that the main reason for this difference is that we chose the anterior transverse arch as a landmark for the stimulator electrode, whereas they chose the distal three-quarters of the sole. However, because there is an inconsistency in the amplitude values given in the studies conducted to date, further studies with standardized methods are needed.

In this study, we sought to ascertain the mean and lower limits of both maximum NCV and negative peak NCV values. This is due to the continued use of both measurements in electrophysiology practice. Although the prevailing view is that SNAP onset latency and maximum velocity are more sensitive to nerve damage, a study of carpal tunnel syndrome demonstrated that the parameter most sensitive to the disease was negative peak latency.^[13] In addition, according to Oh, it is difficult to determine exactly where the SNAP onset latency is, especially in people with nerve damage, and therefore negative peak latency and negative peak NCV need to be measured.^[14] This is the main reason why we measured two separate latencies and two separate NCVs.

Early electrophysiological diagnosis of diabetic neuropathy and TTS still needs to be innovated. Mondelli *et al.* measured the motor conduction sensitivity of the tibial nerve at the level of the tarsal tunnel in patients with diabetic neuropathy and reported an abnormality rate of 64.5%. However, plantar nerve conduction studies were not included in this study.^[15] Altun *et al.* reported that abnormalities in medial plantar nerve conduction studies correlated with those in sural nerve conduction studies in diabetic neuropathy.^[16] Similarly, Løseth *et al.* described that abnormalities in medial plantar nerve conduction studies were susceptible to diabetic neuropathy.^[17] However, these studies methodologically

focus on the sensitivity of the tibial nerve motor and sensory branches to existing polyneuropathy, not on the early diagnosis of polyneuropathy.

As for TTS, many methods have been tried in terms of susceptibility to the disease, and in our opinion, the WPNCs technique described by Hemmi *et al.* is the most promising among them.^[9] Therefore, future studies comparing the latter with previously described electrophysiological methods in the diagnosis of TTS are needed.

It should be noted that this study is subject to certain limitations. The first limitation of WPNCs is its inability to diagnose isolated medial plantar or isolated lateral plantar neuropathies. The simultaneous stimulation of both nerves and the recording of CNAPs may obscure mononeuropathies. Second, WPNCs was only performed on healthy volunteers in this study, and no nerve conduction studies were performed on individuals with polyneuropathy or TTS.

Including pathological groups in future studies will be valuable in terms of diagnostic methods in clinical electrophysiology. In this regard, we plan to compare WPNCs with the method described by Saeed *et al.* in the diagnosis of TTS in the next stage because these methods are based on similar electrophysiological experiments.^[4]

CONCLUSION

This study represents electrophysiology investigation conducted after the definition of the WPNCs method in 2015, with a minor technical modification and with the aim of determining normative values in a larger number of volunteers compared with the initial definitive study. In the present study, the lower limits of the maximum NCVs, negative peak NCVs, and amplitudes of CNAPs obtained with WPNCs in healthy volunteers were quantified according to the 5th percentile (50 m/s, 37 m/s, and 11.69 μ V, respectively). It is anticipated that these lower limit values will be employed in the future for the diagnosis of peripheral nervous system pathologies.

Author contributions

Concept, design, definition of intellectual content, data acquisition: F.E. Literature search, manuscript preparation, manuscript editing: F.E., G.S., M.A. Data analysis, statistical analysis: G.S. Manuscript review: M.A.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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