Published in final edited form as:

Muscle Nerve. 2019 July ; 60(1): 67–71. doi:10.1002/mus.26481.

Quantitative muscle ultrasound in upper extremity mononeuropathies

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Abstract

Introduction: We assessed the potential use of quantitative ultrasound (QUS) in the evaluation of hand muscles affected by upper extremity mononeuropathies.

Methods: The gray scale levels (GSLs) of abductor pollicis brevis (APB), abductor digiti minimi (ADM), and first dorsal interosseous (FDI) of 30 healthy and 30 upper extremity mononeuropathy patients were measured and compared to standard electrophysiological values.

Results: Mean GSL was elevated in 34 APBs of carpal tunnel syndrome patients and 18 FDI of ulnar neuropathy patients (e.g., FDI mean GSL(interquartile range) 31.5(27.3~43.8) arbitrary units for patients and 24.0(23.0~29.0) for healthy subjects ($p=0.020$)). GSL correlated with motor response amplitudes (Spearman's rho (ρ)=-0.39, $p=0.002$ in APB, $\rho=-0.72$, $p=0.002$ in FDI, and $\rho=-0.43$, $p=0.013$ in ADM). The APB GSL correlated with EMG severity and disease duration ($\rho=0.46$, $p<0.001$ and $\rho=0.45$, $p=0.003$).

Discussion: Muscle QUS may serve as a useful tool in upper extremity mononeuropathy evaluation. Further study of this concept is recommended.

Keywords

quantitative ultrasound; upper extremity mononeuropathies; hand muscle; gray scale level; electromyography; nerve conduction

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Ethical Publication Statement:

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

Disclosure of Conflicts of Interest:

None of the authors has any conflict of interest to disclose.

1. Introduction

Over the past 20 years, ultrasound has played an increasing role in the evaluation of many neuromuscular disorders, with its main application being in the evaluation of nerve health¹. For example, it has been found to be highly sensitive to carpal tunnel syndrome² and ulnar neuropathy³, but has also been valuable in identifying areas of nerve inflammation^{4,5}, localized injury⁶, compression⁷, and tumors^{8,9}.

In addition to its use for nerve evaluation, ultrasound has also been studied as a way of quantifying muscle condition. There are two basic approaches for doing this. One approach simply relies upon measuring muscle thickness since atrophy reduces muscle bulk.^{10,11} The second approach is to quantify the echointensity of the muscle, which is expected to increase in most disorders as an increasing proportion of fat and connective tissue leads to increased reflectivity.^{12,13} Quantification of echointensity can be most easily performed via a gray scale level (GSL) analysis, in which an image is converted to a standard photo format, with the relative whiteness/darkness of the image obtained using a commercially available program. An alternative approach is to assess the direct backscatter of the acoustic signal; while this approach is likely to provide “truer” data, since it is not post-processed via various proprietary algorithms, most commercial ultrasound systems do not provide such raw values.^{12,14} Regardless of the approach to quantification, performing such measurements of echointensity is not simple. It requires that the standard device settings and operating procedures including the probe’s location, angle relative to the muscle, and pressure against the muscle be kept consistent across all subjects. In addition, it may be difficult to compare results obtained with different systems.

To date, the main application of muscle quantitative ultrasound (QUS) has been in the evaluation of disease severity and potentially as a biomarker for neuromuscular therapeutic trials in Duchenne muscular dystrophy and other diseases.^{12,15–17} Less studied, however, is the potential for QUS to provide a means for serving as an alternative to standard electromyographic (EMG) evaluation of muscle. While EMG is unquestionably valuable, in many situations it has limitations. For example, subtle degrees of reinnervation can be difficult to identify and the inter-rater reliability of the test is fairly low^{18,19} given its subjective nature. Similarly, some patients cannot readily tolerate the needle electrode examination. Finally, needle EMG is fairly localized in its assessments, and abnormalities restricted to one region of the muscle may be missed due to sampling error.

In this study, we sought to evaluate the potential for QUS to serve as a measure of chronic reinnervation in patients with common upper extremity mononeuropathies of varying severity. Specifically, the aims of this study were to: 1) evaluate if GSL can distinguish between hand muscles of healthy participants and those of patients with upper extremity mononeuropathies; 2) correlate GSL with disease duration; and 3) correlate GSL and electrodiagnostic parameters of nerve conduction and needle EMG.

2. Materials and methods

2.1 Subject information

This prospective study was approved by the Beth Israel Deaconess Medical Center, Boston, MA, institutional review board and all subjects provided written informed consent prior to participation. Both mononeuropathy patients and healthy participants were compensated for their participation.

Mononeuropathy patients.—Thirty patients with typical signs and symptoms of carpal tunnel syndrome (CTS) or ulnar neuropathy at the elbow (UNE) and who met strict electrodiagnostic criteria (described below) were consecutively recruited from the electromyography laboratory of Beth Israel Deaconess Medical Center after undergoing standard testing. Their medical histories were recorded. Standard electrophysiologic criteria confirming a diagnosis of median neuropathy at the wrist, including prolonged median distal motor latency (DML), reduced sensory conduction velocity and abnormalities on comparison studies (e.g., mixed palmar comparison studies and digit 4 sensory comparison studies).²⁰ For ulnar neuropathy at the elbow, slowing of motor conduction velocity across the elbow segment of at least 10.5 m/s as compared to the forearm segment was required, recording from both first dorsal interosseous and abductor digiti minimi.²¹ Sensory abnormalities (e.g., digit 5 sensory response amplitude reduction) were not required. Patients with other neuromuscular disorders were excluded, including those with cervical radiculopathy or brachial plexopathy. If patients were identified as having more than 1 abnormality (e.g. bilateral CTS or UNE and CTS simultaneously), the individual nerve data were collected but analyzed separately.

Healthy participants.—We recruited 30 men and women without a history of neuromuscular disease or any symptoms or history of upper extremity mononeuropathy, aged 18 years and older, as healthy subjects group via Internet advertisement. A detailed neurological examination was performed. Individuals with abnormalities on examination were excluded. Healthy participants did not undergo neurophysiological evaluation.

2.2 Quantitative ultrasound measurements and analysis

All QUS examinations were performed using the Terason t3000 system (Teratech Inc., Burlington, MA) with a 7–12 MHz linear “hockey stick” array transducer. Specific settings included: musculoskeletal mode, size medium, depth 1 cm, focus 0.8 cm, high frequency mode. All other settings, including sliders for gain and time gain compensation, were kept in identical positions for all subjects. The examinations were performed by two trained operators using standardized operating approaches and ultrasound device settings. Cross-sectional images of the abductor pollicis brevis (APB), abductor digiti minimi (ADM) and first dorsal interosseous (FDI) muscles were obtained bilaterally at standard positions (Supplemental Figure 1 and Supplemental Table 1). The probe was placed on the belly of each muscle and rocked back and forth to minimize anisotropy, attempting to keep it as perpendicular to the muscle as possible. Pressure was also minimized to ensure there was no distortion of the underlying muscle architecture, by using sufficient quantities of

ultrasound gel and gently “pulling back” on the probe until a clean image of the muscle was present.

We converted all the images to JPEG files and analyzed them using MATLAB® (The MathWorks, Natick, MA). Median GSL values (arbitrary units, a.u.) were measured using the standard approach, which calculated GSL based on a histogram analysis (defining the darkest level as 0 and the brightest level as 255). We traced the entire region of interest, which comprised the muscle area between subcutaneous tissues and bones, manually using a MATLAB program developed in our lab; the program then selected the most superficial one-third of the region automatically to be used in analysis (Supplemental Figure 2).²² Image analysis was completed by one researcher in our lab who was blinded to the disease/healthy group classification (KQ).

2.3 Electrodiagnostic measurements

All nerve conduction studies were performed using standard approaches. Briefly, for median motor conduction studies, stimulation was performed at the wrist and antecubital fossa with recording electrodes placed over the APB. Ulnar motor nerve conduction studies were performed using the 90° flexed-elbow position, stimulating at the wrist, below the elbow (3 to 4cm distal to the medial epicondyle), and above the elbow (8–10cm from the below-elbow site). Motor responses were recorded with E1 over the belly of each muscle and E2 over the 1st and 5th metacarpophalangeal joints for FDI and ADM, respectively, maintaining a hand temperature of approximately 32°C.

Standard concentric needle EMG was performed. We evaluated the reinnervation qualitatively as the needle EMG score. Reinnervation was graded on a scale from 0 to 3 (0: normal, 1: mild reinnervation and slightly reduced motor unit potential recruitment; 2: moderate reinnervation and moderately reduced motor unit potential recruitment and 3: severe reinnervation with markedly reduced motor unit potential recruitment) according to the observed duration, amplitude and phase of the motor unit action potentials, using a standard “gestalt EMG” approach. Ongoing denervation (fibrillation potentials) was recorded as part of the standard EMG but was not included in this analysis since this was ultimately identified in only a small minority of patients.

2.4 Statistical Analysis

Statistical analyses were performed with SPSS (v. 22.0) software (IBM Corp, Inc., Armonk, NY). Demographic data are presented as mean $\pm$ standard deviation (SD) and compared by unpaired t-test and chi-square test, as appropriate. QUS and electrophysiological variables were uniformly non-parametric in distribution and presented as median (interquartile range) and compared using the Mann-Whitney U test. All correlation analyses, including GSL-EMG correlations, were assessed by Spearman’s rho (ρ). For all tests, $p < 0.05$, two-tailed was considered significant.

3. Results

3.1 Demographic information

The mean age of the patients (18 females and 12 males) was 63.4 ± 12.7 years and the mean age of healthy subjects (12 females and 18 males) was 58.1 ± 9.3 years. The average body mass index of the patients was 31.2 ± 6.3 kg/m² and of the healthy subjects was 28.7 ± 5.1 kg/m². Differences between patients and healthy subjects for age, gender, weight, height and body mass index were not significant ($p=0.12, 0.20, 0.51, 0.33, 0.10$, respectively). Table 1 summarizes the distribution of the CTS and UNE amongst the patients. In two subjects, electrodiagnostic studies recording FDI were not performed and thus data from these two muscles in these two patients were not available. In addition, one FDI image was excluded due to poor image quality. Ultimately, images of 34 APBs, 18 FDIs and 21 ADMs of CTS/UNE patients were included in the analyses; no images were excluded from the healthy participants.

3.2 Comparison of GSL in patients and healthy subjects

Mean GSL was significantly elevated in APB and FDI, but not in ADM. Specifically, for APB, GSL was 24.0(22.0~28.5) a.u. in CTS patients and 22.0(19.0~26.0) a.u. in healthy subjects; GSL in FDI in UNE patients was 31.5(27.3~43.8) a.u. for patients, and 24.0(23.0~29.0) a.u. for healthy subjects. ADM in UNE patients was 25.0(24.0~29.0) a.u. for UNE patients, and 26.0(19.5~28.0) a.u. for healthy subjects (Fig. 1).

Importantly, the GSL values of the unaffected FDIs and ADMs in CTS-only patients, were not different from those in healthy subjects ($p = 0.31$, Mann-Whitney test, and 0.27, t-test, respectively). Similarly, the GSL values of APBs in UNE-only patients were not different as compared to the values in healthy subjects ($p = 0.35$, t-test).

3.3 Correlation between GSL and condition duration

The duration between symptom onset and the performance of QUS was recorded in 24 patients (13 CTS-only patients, 5 UNE-only patients, and 6 with both CTS and UNE). The average disease duration was 3.0(0.7~11.5) years in CTS patients, and 0.4(0.3~2.3) years in UNE patients. The GSL data was positively correlated with disease duration in APBs ($\rho=0.45$, $p=0.003$) but not in FDIs and ADMs ($\rho=0.02$, $p=0.81$, and $\rho=0.61$, $p=0.09$).

3.4 Correlation between GSL and Electrodiagnostic parameters

The raw electrodiagnostic data are shown in Table 2. The correlation analyses between GSL and electrodiagnostic parameters in APB and FDI are shown in Fig. 2 and 3, respectively. CMAP amplitudes were significantly correlated with the muscle GSL data for all 3 muscles ($p<0.05$). Surprisingly, the median nerve DML was not significantly correlated with the APB GSL, although ulnar nerve DML correlated to FDI GSL, though not APB. The across-elbow motor conduction velocity of the UNE was negatively correlated with the GSL data of FDI. The UNE forearm conduction velocity was negatively correlated with the GSL data of ADM ($\rho=-0.36$, $p=0.020$). The needle EMG scores positively correlated with the GSL data in APB, but not for FDI and ADM.

4. Discussion

In this study, we provide early evidence that QUS values can provide a means of quantifying muscle neurogenic change in two common upper extremity mononeuropathies. This study adds to one earlier study assessing denervation in upper extremity hand muscles¹¹; however, in that study, only patients with more severe disorders were included. Our study, in contrast, represented a more typical population of people presenting to an electromyography laboratory for evaluation of upper extremity mononeuropathy with most having only mild-to-moderate degrees of reinnervation on needle EMG.

The most relevant finding was the observed elevation in GSL in APB and FDI in CTS and UNE patients, respectively, and the corresponding fact that these values were not elevated in unaffected muscles. Another factor supporting this conclusion is that the GSL corresponded to CMAP amplitude across all three muscles; APB GSL's strong correlations with APB EMG score and the disease duration were also reassuring. Somewhat unexpectedly, we found that FDI GSL appeared to be more robustly associated with the electrophysiologic data than ADM GSL in UNE patients. The absence of a significant correlation between APB GSL and median nerve DML was unexpected, as was the significant correlation between FDI GSL and ulnar nerve DML. One possible explanation for these inconsistencies is the fact that the CTS patients had milder abnormalities than the UNE patients. This is reflected in the normal CMAP values for all CTS patients and the minimal amount of reinnervation present on needle EMG (the highest reinnervation score on EMG in CTS was 1.0 as compared to the UNE patients, which was 3.0).

The mechanism underlying increasing muscle echointensity in patients with upper extremity mononeuropathy deserves explanation. Ultrasound does not detect actual reinnervation of the muscle, as does needle EMG. Rather, ultrasound echo intensity is sensitive to associated alterations including the deposition of fat and connective tissue in the muscle, a histological feature that generally accompanies only chronic neurogenic change²³. Alternatively, neurogenic atrophy may also reduce the overall contribution of healthy muscle fibers to the image, leaving the more reflective elements of the muscle (fascial planes and supporting connective tissue). Subacute injury to a nerve that produces substantial change on needle EMG may show relatively little in terms of QUS parameters. In fact, early nerve injury may be associated with mild muscle edema resulting in a reduced rather than an increased GSL²⁴. Thus, all of these factors could explain some of the inconsistencies observed between GSL and electrophysiological parameters.

Another interesting fact was that FDI GSL was more robustly associated with electrodiagnostic features than was ADM in patients with UNE. There may be several explanations for this. First, studies have suggested that nerve injury can induce inconsistent effects on GSL across muscles²³. Second, one study suggested a slightly higher sensitivity of FDI than ADM to UNE²⁵. An alternative explanation for this may be that it is easier to obtain consistent/accurate images of FDI as compared to ADM. Both FDI and ADM were imaged with the hand flat, palm down. It is very simple to place and hold the transducer over FDI since it is flat. However, ADM has a rounded shape, and when performing transverse measurements with light pressure, the transducer has a tendency to glide or roll off. Given

the muscle's shape, it is also more challenging to maintain a consistent application of ultrasound gel.

It is important to point out that while we did identify a number of significant differences, for example in the echo intensity in the APB of CTS vs. healthy subjects, there was also considerable overlap. This could reflect the general insensitivity of QUS techniques to minor alterations in muscle health. However, it could also reflect the fact that mild CTS is often not accompanied by significant muscle alteration. Indeed, 45% of the APBs had no reinnervation on needle EMG, as compared to FDI (28%) and ADM (6%).

This study has a number of limitations. First, the number of patients was relatively small, which could explain some of the inconsistencies in our results, and also raising the possibility that the analyses may suffer from Type 2 statistical error. Second, since we performed our statistical analyses using individual nerve/muscle data with multiple values often coming from a single patient, these analyses are not independent, and have the potential for falsely elevating the statistical significance of some of these findings. Third, we were not blinded to disease diagnosis when we collected the ultrasound data (although the individual collecting the data was not made specifically aware of whether the patient had CTS, UNE, or both). Finally, we did not perform any form of quantitative EMG analysis^{26,27} or motor unit number estimation²⁸. Such an analysis would have been preferable since it would have provided quantitative values with which to compare the QUS data.

Despite these limitations, this study found intrinsic hand muscle GSL was increased in patients with upper extremity mononeuropathy as compared to healthy individuals, and muscle echointensity levels of patients with upper extremity mononeuropathy correlated with disease duration and a number of electrophysiologic parameters. These findings suggest that QUS may be considered a potentially useful procedure for the standard assessment of these disorders. Given the relatively small sample size, additional dedicated study of this question in a larger number of individuals is recommended.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements:

This work was funded by the National Institute of Health grant K24NS060951. Yun Wang thanks the Program of Study Abroad for Young Physicians sponsored by Beijing Chaoyang Hospital, Beijing, China.

Abbreviations

ADM	abductor digiti minimi
APB	abductor pollicis brevis
CMAP	compound muscle action potential
CTS	carpal tunnel syndrome

DML	distal motor latency
EMG	electromyography
FDI	first dorsal interosseous
GSL	gray scale level
QUS	quantitative ultrasound

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Figure 1.

Comparison of gray scale level (GSL) values (arbitrary units, a.u.): GSL value of abductor pollicis brevis in patients with carpal tunnel syndrome and healthy subjects; GSL values of first dorsal interosseous and abductor digiti minimi in patients with ulnar neuropathy at the elbow and healthy subjects.

Figure 2. Correlation between gray scale level (GSL) values (arbitrary units, a.u.) and electrodiagnostic parameters of abductor pollicis brevis in patients with carpal tunnel syndrome.

Figure 3. Correlation between gray scale level (GSL) values (arbitrary units, a.u.) and electrodiagnostic parameters of first dorsal interosseous in patients with ulnar neuropathy at the elbow.

Table 1.

The disorder category of patients

Disorder	Number of subjects/bilateral involvement	Number of muscles studied		
		APB	FDI	ADM
CTS-only	14/6	20	-	-
UNE-only	6/1	-	6	7
UNE together with CTS	10/4	14	12	14
Total	30	34	18	21

Abbreviations: carpal tunnel syndrome (CTS), ulnar neuropathy at the elbow (UNE), abductor pollicis brevis (APB), first dorsal interosseous (FDI), abductor digiti minimi (ADM).

Table 2.

Overview of the electrodiagnostic parameters in affected muscles.

		CTS	UNE	
Electrodiagnostic parameters		APB median(IQR)	FDI median(IQR)	ADM median(IQR)
CMAP (mV)	wrist to muscle	6.9(6.2~8.4)	10.3(2.9~13.2)	8.5(6.5~9.9)
DML (ms)	wrist to muscle	4.6(4.2~6.2)	4.1(3.8~4.6)	3.2(3.0~3.4)
MCV (m·s ⁻¹)	Below elbow to wrist	51.1(50.3~55.0)	51.6(50.3~56.8)	53.1(50.1~56.3)
	Above elbow to below elbow	-	37.5(30.9~41.2)	34.9(30.9~41.8)
Needle EMG scores		1.0(0~1.0)	2.0(0.3~3.0)	2.0(1.0~3.0)

Abbreviations: carpal tunnel syndrome (CTS), ulnar neuropathy at the elbow (UNE), compound muscle action potential (CMAP), distal motor latency (DML), motor conduction velocity (MCV), electromyography (EMG), abductor pollicis brevis (APB), first dorsal interosseous (FDI), abductor digiti minimi (ADM), and interquartile range (IQR).