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Electrical impedance myography for discriminating traumatic peripheral nerve injury in the upper extremity

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HIGHLIGHTS

- Hand held electrical impedance myography (EIM) of hand muscles was used to test muscle atrophy after traumatic peripheral nerve injury.
- EIM reactance and phase values of the affected muscles were consistently lower than those of healthy muscles.
- Severity of peripheral nerve injury determines the extent of muscle atrophy.

ABSTRACT

Objective: To evaluate the potential of electrical impedance myography (EIM), which is sensitive to the changes in muscle structure and physiology, in discriminating traumatic peripheral nerve injury (TPNI) in the upper extremity. To identify factors that primarily influence muscle atrophy secondary to nerve injury.
Methods: Thirty-nine patients with TPNI underwent EIM measurement and standard electromyography tests for multiple muscles in the upper extremity. The side-to-side differences in EIM parameters were calculated for each subject and compared with the compound motor action potential (CMAP) amplitude, which is a measure of injury severity, and the time since injury.
Results: The reactance and phase values of the affected muscles were consistently lower than those of healthy muscles, with an average side-to-side difference of approximately −50% ($p < 0.001$) and −45% ($p < 0.001$), respectively. The CMAP amplitude, rather than the time since injury, had a greater effect on the side-to-side difference of phase values.
Conclusions: EIM discriminates TPNI by revealing asymmetries in reactance and phase values. The severity of injury had a larger influence than the time since injury on muscle atrophy secondary to nerve injury.
Significance: These results demonstrate the putative use of EIM in discriminating TPNI and deserves further study.

1. Introduction

Traumatic peripheral nerve injury (TPNI) is common in clinical practice, where more than 5% of patients are annually admitted to a level-one trauma center with concurrent TPNI (Robinson, 2004; Taylor et al., 2008). Typically seen in young adult men, TPNI occurs

Abbreviations: APB, abductor pollicis brevis; ADM, abductor digiti minimi; CMAP, compound motor action potential; EDC, extensor digitorum communis; EIM, electrical impedance myography; EMG, electromyography; MRI, magnetic resonance imaging; MNI, median nerve injury; NCS, nerve conduction study; RNI, radial nerve injury; TPNI, traumatic peripheral nerve injury; UNI, ulnar nerve injury.

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after a variety of traumatic events, including penetrating injury, crush, stretch, and ischemia (William, 2008). Severe nerve injury can have devastating effects on the quality of a patient's life. The classic symptoms of TPNI are sensory and motor function defects, which can cause full paralysis of the affected extremity or refractory neuropathic pain (Houdek and Shin, 2015). A great majority of injuries occur to peripheral nerves in the upper extremity, most commonly the median, ulnar, and radial nerves (Noble et al., 1998; Kouyoumdjian, 2006).

Electromyography (EMG) and nerve conduction study (NCS) are helpful in diagnosing TPNI (Dianna and Shawn, 1999; Aminoff, 2004). NCS can be applied immediately to localize nerve injury, EMG is typically withheld till 3–6 weeks post-injury since no degenerative change will occur during this period (Houdek and Shin, 2015).However, NCS and EMG have a limited ability to distinguish morphologic changes related to a particular type of nerve injury. Compared with electrodiagnostic tests, ultrasound and magnetic resonance imaging (MRI) are used to provide this information in a painless way (Craig et al., 2013). Ultrasound is valuable in the care of acute TPNI, when diagnosing nerve continuity (Chiou et al., 2003; Hollister et al., 2012; Padua et al., 2013), while MRI can be used to describe nerve lesions in areas that are difficult to localize using electrodiagnostic studies or visualize using ultrasound (Grant et al., 2002; Martin and Guido, 2005; Nilsson et al., 2009). However, owing to its high cost and slow speed of examination, MRI is still not routinely used to assess peripheral nerve injuries.

Electrical impedance myography (EIM) is a relatively new, painless, and non-invasive method for the evaluation of neuromuscular diseases (Shiffman et al., 1999; Rutkove et al., 2002). EIM transmits a low-intensity and high-frequency alternating current through the muscle and measures the consequent surface voltage (Rutkove, 2009). The following EIM parameters: resistance (R), reactance (X), and phase (θ), which is calculated by the formula $\theta = \arctan(X/R)$, can be used to evaluate the state of muscles (Rutkove et al., 2002; Tarulli et al., 2005; Rutkove and Darras, 2013; Zaidman et al., 2015). Although the development of EIM is still at a relatively early stage, it is sufficiently reproducible and sensitive for use in monitoring the progression of a variety of neuromuscular diseases, such as myopathies (Tarulli et al., 2005), radiculopathies (Rutkove et al., 2005; Spieker et al., 2013), spinal muscular atrophy (Rutkove et al., 2010, 2012b; Li et al., 2014), Duchenne muscular dystrophy (Rutkove and Darras, 2013; Schwartz et al., 2015; Zaidman et al., 2015), and amyotrophic lateral sclerosis (Wang et al., 2011; Rutkove et al., 2012a, 2014; Pacheck et al., 2016). Further, as demonstrated by rat models where the impact of neurogenic injury on the electrical properties of skeletal muscle was assessed using EIM, it is sensitive enough to detect neurogenic injury (Nie et al., 2006; Ahad and Rutkove, 2009).

In the current study, using a convenient and improved handheld array, we assessed if individual side-to-side differences of EIM parameters could be useful for discriminating TPNI in the upper extremity. This study included single nerve injuries, which included median nerve injury (MNI), ulnar nerve injury (UNI), or radial nerve injury (RNI), and compound nerve injury. Further, we compared EIM values to EMG data and the time since injury, to identify factors that have a primary influence on muscle atrophy secondary to nerve injury.

2. Methods

2.1. Subjects

Only patients with unilateral TPNI in the upper extremity were recruited for the current study through the Department of Hand Surgery, HuaShan Hospital of Fudan University. All prospective subjects were pre-screened to exclude those who were pregnant, had an implanted electrical device (e.g. pacemaker), or were undergoing dialysis. Patients were also excluded if they had a concomitant neuromuscular or other medical condition. The protocol was approved by the Institutional Review Board of the HuaShan Hospital of Fudan University, and all participants provided written informed consent.

2.2. Electrical impedance myography measurements

Using a blinded protocol design, EIM measurements were taken without prior knowledge of EMG data or clinical diagnosis of pre-screened patients. Patients were asked to completely relax and sit comfortably in a chair, with their arms resting on an examination table. EIM measurements were taken using an Imp SFB7 system (Impedimed, Inc., Sydney Australia) with a hand-held probe (Fig. 1a). The resistance (R), reactance (X), and phase (θ) parameters were obtained, which ranged from 3 kHz to 1 MHz. Three muscles in the upper extremity, including the abductor pollicis brevis (APB), abductor digiti minimi (ADM), and extensor digitorum communis (EDC) were assessed for each subject, on both the affected and healthy sides. There were no wounds on the muscles that were tested.

The hand-held EIM probe was constructed as follows: four stainless steel electrodes were attached to a polyethylene bar, which in turn was mounted to a round polyethylene handle. They corresponded to the current-injecting and voltage-measuring electrodes, respectively (Narayanaswami et al., 2012). Two types of EIM probes were used depending on the size of muscles: a large one for the EDC and a small one for the APB and ADM (Fig. 1a). In the large probe, each stainless steel electrode was 7.5 mm wide and 25 mm long and was placed in a linear array. The outer and inner electrodes were 60 and 30 mm apart, respectively. In the small probe, each stainless steel electrode was 5 mm wide and 10 mm long and was placed in a linear array. The outer and inner electrodes were 40 and 20 mm apart. The connecting wires from the four electrodes were contained in the handle of the probe and the lead plugs from the impedance device were at the proximal handle end. Prior to applying the probe, dead skin over the muscle was removed using medical alcohol to ensure good electrical contact.

To improve the ability of the dry electrode to record biopotential signals, a variety of micro-needle electrodes, which are solid, hollow, barbed, and flexible, have been developed to decrease the electrode–skin contact impedance and noise (Yu et al., 2009; Hsu et al., 2014; Arai et al., 2015; Chen et al., 2016; Li et al., 2016). The micro-needles can pierce through the stratum corneum, increasing the electrode–skin contact area. Since the skin above the muscles are not a smooth plane, the flexible micro-needle electrode array provides the best electrode–skin contact. In a word, the micro-needle electrodes could decrease the contact impedance sharply and significantly improve biopotential recordings, and they were used in electrocardiograms, electroencephalograms and EMG. However, the properties of the materials used for micro-needle electrodes, such as silicon and polymeride, were not favorable to assemble into an EIM probe. Furthermore, subjects were less receptive to the micro-invasive manner of micro-needle electrodes, for worrying about the possibility of cross infection.

Therefore, a micro-pillar structure was manufactured on the surface of the stainless steel electrodes using a laser processing technique. Fig. 1b shows a scanning electron microscope image of the resulting micro-pillar array. The diameter and height of each micro-pillar was approximately 200 and 100 μm, respectively. Compared with the smooth electrode surface, the micro-pillar structure is capable of rapidly increasing the electrode–skin con-