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Conduction velocity distribution estimation using the collision technique—Theory and simulation study

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Abstract

Current nerve conduction studies (NCS) are influenced by the activity of the largest active fibers, making it difficult to assess the state of smaller nerve fibers. This study is aimed at alternative diagnostic techniques for assessing carpal tunnel syndrome (CTS). A conduction velocity distribution (CVD) estimator based on the collision technique that incorporates volume conductor modeling is proposed and discussed in this paper. Simulations were run to evaluate the accuracy of the CVD estimator and compare its performance with previous CVD estimators based on the collision technique. Results show the improved accuracy of the proposed approach, which is able to provide estimates with a percent mean square error (PMSE) lower than 1.1% for all CTS cases studied and lower than 2% in the presence of additive white Gaussian noise. Simulations also showed that conduction slowing in the carpal tunnel (CT) segment is detected by the proposed technique and displayed as an increase in the number of low velocity fibers. Results suggest that both CVD estimator and amplitude parameter proposed can help detect the severity of CTS in a patient more accurately than current NCS.

Keywords: Nonnegative least-squares estimation; Volume conductor modeling; Collision technique; Nerve conduction studies; Conduction velocity distribution

1. Introduction

Carpal tunnel syndrome (CTS) is a nerve conduction syndrome caused by localized compression of the median nerve at the wrist. CTS is generally detected using electrophysiological testing such as standard nerve conduction studies (NCS). NCS are performed by placing stimulating electrodes at a distance from the recording electrodes and measuring the peak latency of the compound nerve action potential (CNAP) recorded. The sensory orthodromic response is generally of small amplitude and requires averaging [1]. Typical measurements made are amplitude, area under the waveform, latency and conduction velocity (CV). An average sensory CV of 45 m/s or less indicates the presence of CTS [2,3].

NCS evaluate the function of large myelinated nerve fibers with the highest CV, *i.e.* A beta fibers [2,4]. Selective evaluation of nerve fibers based on their diameter or CV is not feasible with these techniques. According to the literature [4], severity of CTS progresses from large nerve fibers to small nerve fibers. This is not a surprising finding given that NCS available are able to evaluate the largest fibers active at the time of recording. An early deficit in the activity of smaller nerve fibers will likely go unnoticed since the contribution of larger fibers to the CNAP recorded is significantly bigger than that coming from the smaller fibers [5]. Hence, a method to assess the diameter or CV of the active nerve fibers traversing the carpal tunnel will improve current CTS diagnostic techniques.

Characterizing a nerve in terms of the probability density function (pdf) that describes the distribution of active fibers across a velocity interval can be done by estimating its CV distribution (CVD). If reliable CVD estimates for the median nerve fibers traversing the carpal tunnel are obtained this will be a useful parameter to describe the nerve fibers being affected in a CTS patient. A new method for estimating CVD is proposed in this paper. The estimation of the electrical source needed for the CVD estimator makes use of a deconvolution approach applied to signals recorded using the collision technique as will be described in Section 3.

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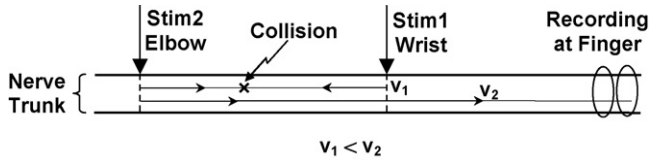

Fig. 1. Stimulation-recording collision setup. Stimulation pulse 1 delivered at the wrist, stimulation pulse 2 delivered at the elbow site following a short delay (ISI). Collision of slow fibers, *e.g.* v_1, happens between elbow and wrist. Action potentials from faster fibers, *e.g.* v_2, travel successfully from elbow to finger recording site.

The collision technique can be used to selectively activate nerve fibers of different diameters by varying the delay between two stimuli—a distal supramaximal stimulus and a delayed proximal stimulus [3]. There are two stimulation channels placed on the skin surface, one at the wrist (the distal) and another at the elbow (the proximal). The proximal and distal CNAPs are recorded using a bipolar channel consisting of two surface ring electrodes placed at the middle finger. The inter-stimulus interval (ISI) is the time interval between the delivery of the wrist stimulus pulse and the delivery of the elbow stimulus pulse. When the ISI is relatively large, the proximal CNAP does not collide with the distal CNAP, hence a response from all the nerve fibers activated by the elbow stimulus pulse is obtained. When the ISI is gradually decreased, the contribution from small nerve fibers reduces as the slow traveling action potentials generated at both stimulation sites start colliding and only the faster traveling action potentials get through to the recording electrodes placed on the finger (see Fig. 1).

Of the action potentials getting through the one with the lowest CV is determined by the ISI value. This lowest velocity value is calculated as [3]:

$$\mathrm{CV} = \frac{D + 3.2}{\mathrm{ISI} - 0.37} \tag{1}$$

where CV is the conduction velocity in m/s, D the distance in mm between the two stimulation sites, *i.e.* wrist and elbow, ISI is the time in ms between delivery of wrist and elbow stimulation pulses.

2. Signal modeling; SSFAP and CNAP

The CNAP response is the raw data from which the CVD is estimated therefore the CNAP modeling is an essential part of the CVD estimation technique. The CNAP is made of the superposition of single fiber responses, or single fiber action potentials (SFAP). In the approach proposed here signals are recorded at the skin surface requiring a description of the surface SFAP (SSFAP). The SSFAP is given as the convolution of the electrical source with tissue filter impulse response functions [5,6]:

$$\mathrm{SSFAP}(t, v) \cong K_1 s(t) * h\left(t - \frac{d}{v}, v\right) \tag{2}$$

where $h(t, v) = t/[(r/v)^2 + t^2]^{3/2}$ is the tissue filter impulse response and $s(t) = \partial V_\mathrm{m}(t)/\partial t$ the electrical source, $V_\mathrm{m}(t)$ the fiber membrane potential as an AP is generated, and * is the convolution operator, K_1 is a constant accounting for the electrical conductivities of the media, r is the distance from fiber axis to recording point, *i.e.* fiber depth, d is the distance traveled between stimulation and recording site, v is the CV of the action potential, and t is the time variable.

CNAP signals picked up by electrodes were expressed as the superposition of the SSFAP contributions. The elicited activity has been modeled as a linear summation of the temporally dispersed SSFAPs. Further, the fibers can be grouped into delay bins and the amplitude contribution of each class is assumed to be proportional to number of fibers in that class. Hence, the CNAP can be written as [5]:

$$\mathrm{CNAP}(t) = \sum_{i=1}^{M} m_i \mathrm{SSFAP}(t, v_i) \tag{3}$$

where M is the total number of delay bins, m_i the number of active fibers in bin i, bin i, or class i, groups fibers within a small range of delays $[\tau_i - \delta/2, \tau_i + \delta/2]$, $v_i$the CV representative of fibers in bin i, $\tau_i = d/v_i$ the delay corresponding to a fiber with velocity v_i, and δ is the delay bin width.

3. CVD estimator

3.1. Source estimator

A description of the electrical source used by the CVD estimator is essential. This source differs from one individual to another. We estimate it by measuring the CNAP contribution of a particular velocity range of fibers from the subject under study. By subtracting consecutive CNAPs obtained as the ISI is progressively reduced the CNAP contribution from fibers belonging to a certain velocity interval $[v_\mathrm{low}, v_\mathrm{high}]$ can be isolated (see Fig. 2).

Two elbow CNAPs containing the contribution of fibers with velocities greater than $v_\mathrm{low} = d/(\tau_i + \delta/2)$, CNAP_1, and greater than $v_\mathrm{high} = d/(\tau_i - \delta/2)$, CNAP_2, are obtained. This is achieved using the collision technique with ISI values corresponding to v_low and v_high, as determined from Eq. (1). The two CNAPs are subtracted to get the CNAP contribution of active fibers in the velocity range $[v_\mathrm{low}, v_\mathrm{high}]$. This CNAP difference can be written as

$$\mathrm{CNAP}_\Delta(t) = \sum_{v_i = v_\mathrm{low}}^{v_\mathrm{high}} \mathrm{SSFAP}(t, v_i) \tag{4}$$

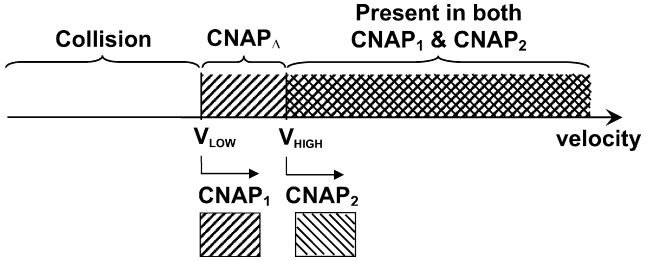

Fig. 2. The CNAP difference ($\mathrm{CNAP}_\Delta = \mathrm{CNAP}_1 - \mathrm{CNAP}_2$) contains the contribution from nerve fibers with velocities larger than v_low and smaller than v_high.