Spectral and Spatial Features of Diffuse Optical Signals in Response to Peripheral Nerve Stimulation

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Abstract

We investigate possible origins to the optical response to electrical stimulation of peripheral nerves. Spatial dependent maps show repeatable positive and negative signals measured on the sural nerve. Vascular occlusion experiments show optical responses due to median nerve stimulation does not follow irradiance changes measured on the capillary bed during venous or arterial occlusion. Broadband measurements show that coupling changes exhibit featureless spectra and that stimulated spectra below and above motion threshold can be modeled as blood vessel displacements. We conclude that the most likely origin of the optical response is blood vessel displacement associated with muscle twitch.

Introduction

We have reported that fast (~0.1 ms) electrical stimulation of peripheral nerves triggers a non-invasively detected optical response on a time scale of ~100 ms[1]. We have then investigated the spatial characteristics as well as the diagnostic potential of such optical response to peripheral nerve stimulation, finding a co-localization with the sensory nerve action potential (SNAP)[2], and a delayed response in patients affected by diabetic neuropathy[3]. In the present work, we report further studies on the spatial and spectral dependencies of these optical signals in an effort to understand their origins.

There have been several studies of optical signals in the central nervous system, either the brain[4-5] or the spinal cord[6-7], induced by peripheral nerve stimulation. Non-invasive studies in the human brain have been aimed at detecting both a hemodynamic response to brain stimulation, on a time scale of seconds, and a fast optical response on the same time scale of ~100 ms as evoked potentials[8].

A previous non-invasive study of optical signals in response to peripheral nerve stimulation specifically aimed at detecting an optical response on the same time scale (~ms) of the median nerve action potential [9]. In this study, Lebid et. al. presented concurrent electrical and optical measurements with a fast sampling rate of 2 kHz, but were not able to detect an optical signal on the millisecond time scale of the sensory nerve action potential [9].

Methods

We used an electromyogram to stimulate the sural and median nerves. For spatially resolved measurements, a two wavelength tissue spectrometer (690,830nm) to collect spatially resolved measurements at 12 source locations (Fig. 1) on the right sural nerve of 4 healthy human subjects.

For vascular occlusion experiments, we used a pressure cuff on the upper arm of 2 subjects to induce a pressure of 50mmHg for venous occlusion and 220/150mmHg for arterial occlusion, measuring the tissue response as well as the stimulated response of the median nerve. The setup of the median nerve experiments includes the vascular occlusion setup (Fig. 2a).

There are 4 phases of the vascular occlusion experiments. Phase 1 is the baseline. Phase 2 is during electrical stimulation. Phase 3 is during electrical stimulation plus venous or arterial occlusion. Phase 4 is the release and recovery of occlusion during electrical stimulation.

For broadband spectral measurements, we explored the stimulated signal as well as the effects of fiber coupling on a tissuelike phantom and skin using a xenon arc lamp and CCD (Fig. 2b).

Results/Discussion

Spatially resolved results are shown in Fig. 1(a-d) and exhibit positive signals mostly between 12o'clock to 4 o'clock clockwise positions. This shows that our signal could not be due to a dilation or constriction and a spatially localized combination of the two is unlikely.

Arterial occlusion results (Fig. 3a,b) show that with tissue properties changing drastically (~20% increase in 830nm and ~30% decrease in 690nm) the stimulated signal does not follow and shows a slight decrease ~0.3% in both wavelengths from pre-occlusion amplitudes. Venous occlusion results (Fig. 3c,d) show that the tissue properties decrease ~60% of 690nm, ~40% of 830nm, the stimulated response increases slightly ~0.2% from pre-occlusion amplitudes.

Broadband results show that coupling changes in tissuelike phantom and skin both show featureless spectra (Fig. 4a,b). Stimulated spectral response below and above motion threshold can be modeled as a 100μm, and 1mm displacement, respectively (Fig. 4 c,d).

Conclusion

Possible origins of optical response to peripheral nerve stimulation:

1.Blood in capillary bed and small vessels
- ➢No: stimulated response does not follow vascular-occlusion-induced changes in tissue optical properties

2. Vascular dilation or constriction
- ➢Unlikely: optical response shows both positive and negative signs

3. Blood vessel displacement
- ➢Likely: Spatially dependent and consistent with positive and negative responses
- ➢Not dependent upon optical properties of background tissue

4.Fiber-skin optical coupling
- ➢Unlikely, but may contribute to optical signals
- ➢Wavelength dependence in a number of cases
- ➢No visible skin motion during most experiments

Fig. 1 Spatially Resolved Measurement Setup

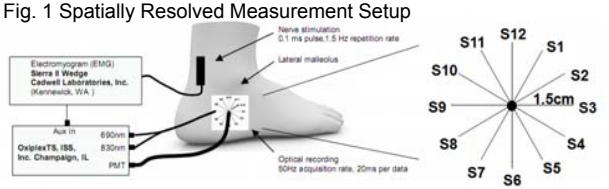

Figure 1 shows the experimental setup of the spatially resolved measurements and the 12 source positions (inset).

Fig. 2 Spatially Resolved Results

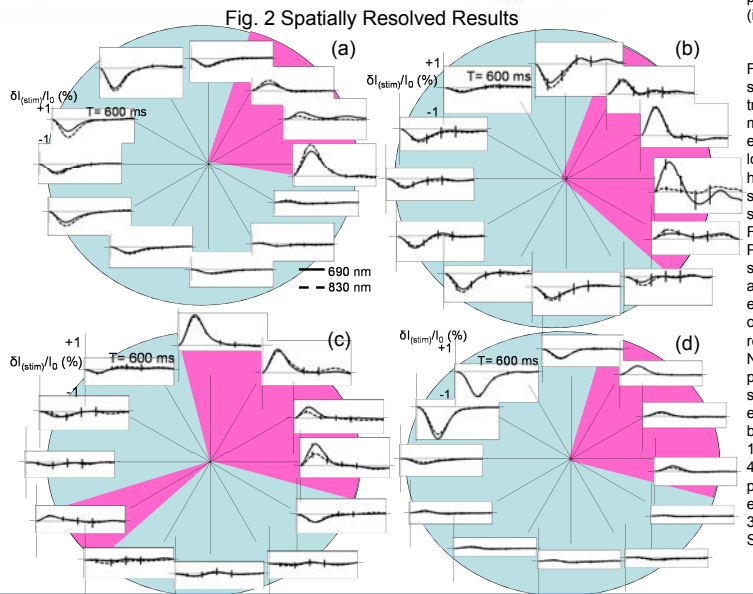

Figure 2 shows time traces measured at each spatial location of 4 human subjects, shown in Fig.2(a-d). Pink highlights show spatial areas that exhibit positive optical responses. Notice all positive signals are exhibited between 12o'clock thru 4 o'clock positions except subject 3 (Fig.2c) at S8.

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Fig. 2 Spectral Measurement Setups

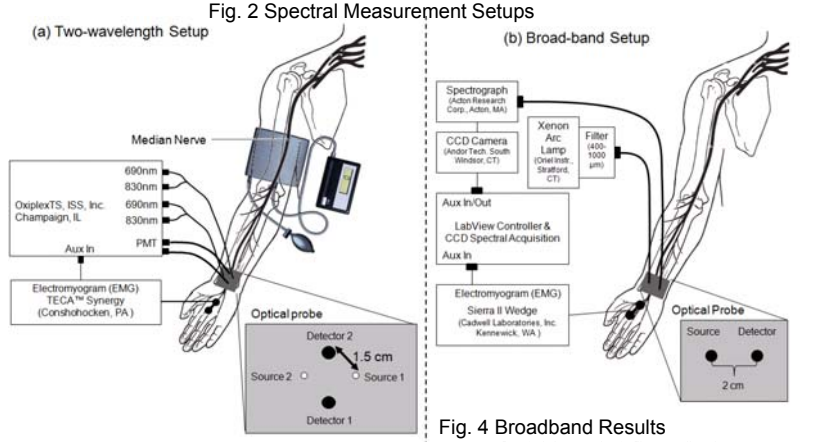


Fig. 3 Vascular Occlusion Results

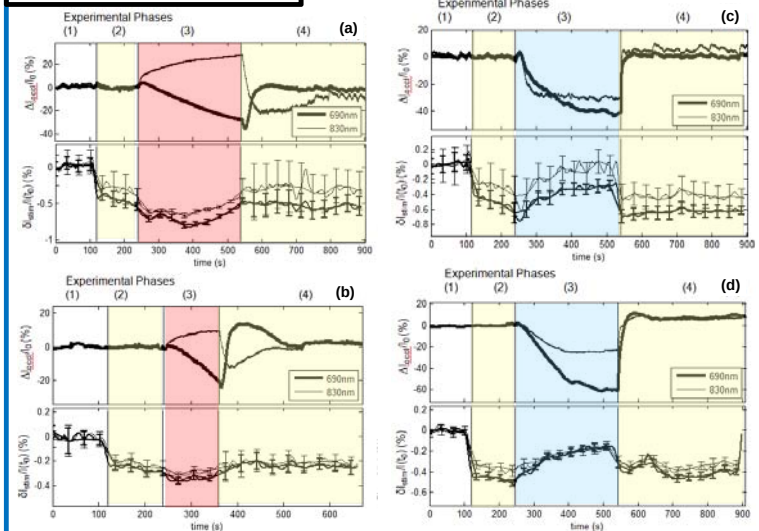
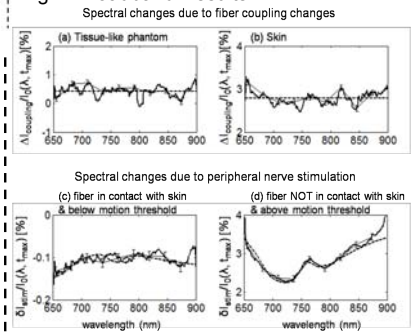


Figure 3 shows the vascular occlusion results of 2 subjects with arterial occlusion (Fig.3a,b) and venous occlusion (Fig.3c,d) Top panels show the background tissue response $\Delta I_{occl}/I_0$, and lower panels show the maximum stimulated responses, $\delta I_{stim}/I(t_0)$ of the source-detector area exhibiting the largest stimulated 1.5 Hz frequency.

Fig. 4 Broadband Results



Broadband spectra at the maximum response time of subject_6 showing (a) $\Delta I_{coupling}/I_0(\lambda, t_{max})$, in fiber-phantom coupling (solid) and its average (dashed), (b) $\Delta I_{coupling}/I_0(\lambda, t_{max})$, in fiber-skin coupling (solid) and its average (dashed), (c) relatively featureless stimulated spectral response with fiber in contact with skin, $\delta I_{stim}/I(\lambda, t_{max})$, (solid) and modeled blood vessel displacement of 100μm (dashed), (d) stimulated optical response with fiber not in contact with skin, $\delta I_{stim}/I(\lambda,t_{max})$, showing characteristic hemoglobin absorption peaks (solid) and corresponding modeled 1mm blood vessel displacement spectra (dashed). Solid lines show smoothed spectra using a 20 nm moving average. Error bars show standard error of unsmoothed spectra.

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