MEASUREMENT OF COMPLEX IMPEDANCE SPECTRA OF IMPLANTED ELECTRODES

K. Yoshida, A. Inmann, and M. K. Haugland

Center for Sensory-Motor Interaction
Aalborg University

Fredrik Bajers Vej 7 D-3, DK-9220 Aalborg Ø, Denmark

ABSTRACT
The overall objective of this work is to determine whether increased information can be extracted about the condition of the implanted tissue and tissue/electrode interface by non-invasive analysis of the complex impedance of implanted electrodes. As a first step towards this objective, we have developed a method of quickly determining the complex impedance spectra. A broadband current waveform was injected through the test electrode. The injected current and resulting voltage waveforms were sampled and the transfer functions of these waveforms were digitally calculated to determine the complex impedance spectrum. The approach was applied to known linear devices as resistors and RC networks as a validation of the method. Finally, the method was applied to surface and implanted electrodes in an acute animal preparation. Two types of broadband waveforms were tested: broadband noise and frequency sweep. We found that the technique was able to successfully measure the complex impedance of purely resistive and RC networks using either test waveform. The frequency sweep waveform resulted in generally cleaner impedance spectra compared to those generated the noise waveform. Preliminary results from our in-vivo tests with implanted cuff electrodes, surface electrodes and needle electrodes were found to be qualitatively consistent with those found in the literature using pure tone measurements.

Keywords: complex impedance, implanted electrodes, technique development

INTRODUCTION
The measurement of electrode impedance has become a common method of non-invasively determining the continuity and condition of chronically implanted electrodes in human and in animal models. A standard technique that is used is to pass a small amplitude (~1µA), constant current, 1 kHz sine wave through the electrode and measure the peak to peak amplitude of the voltage [1,2]. Simple division of the measured voltage amplitude by the amplitude of the injected current gives the magnitude of the impedance of the electrode. The phase information of the complex impedance is typically ignored. The processes involved at the electrode/tissue interface are complex and not purely resistive. Moreover, changes to this interface or to the tissue by biological processes may express themselves as distributed changes in the impedance spectrum. Recently, Williams et al [3] have shown evidence that the real component of the complex impedance may have correlates to physiological changes in the electrode/tissue interface of chronically implanted wire intracortical electrodes.

One limiting factor to the use of impedance spectrum measurements is the difficulty in making the measurement. The measurement of complex impedance spectrum using instruments designed for single frequency measurements is often a laborious and time consuming process. We have developed a method of quickly measuring complex impedance spectra. The present paper discusses this method and its application to the measurement of implanted nerve electrodes.
METHODS

Low amplitude (~100nA) broadband current waveform was injected through the test electrode. Both the injected current and the resulting voltage waveforms were digitally sampled for 20-30 seconds at 30kHz. Fast Fourier transforms of these sampled waveforms were then calculated. Finally, the complex Fourier coefficients of the voltage waveform were divided by those of the current waveform to derive the complex impedance of the electrode. Although any broad bandwidth waveform could be used with this technique, we limited our tests to two: constant amplitude frequency sweep (0.1 Hz to 10 kHz) and white noise.

The technique was tested on a purely resistive impedance and a simple RC filter (10kΩ parallel to 0.1µF) to determine if it would be able successfully measure their complex impedance. Following the test on simple linear components, the method was applied to commercial self adhering gel surface electrodes (2811, Medicotest A/S, Denmark), percutaneous needle electrodes (18G stainless steel), and implanted cuff electrodes.

RESULTS

The complex impedance spectrum of purely resistive components and simple RC networks were reliably resolved using the method. A typical example of a spectrum from a simple RC filter is shown below in figure 1.

Fig. 1. Magnitude and phase of impedance recorded from a simple RC filter (10 kΩ parallel to 0.1µF) using two modes of broad bandwidth current, frequency sweep (black) and broad bandwidth noise (dashed). These are shown compared to the theoretical curves (gray).

Fig. 2. Magnitude and phase of the impedance recorded from a cuff electrode implanted acutely around the sciatic nerve of an anaesthetised rabbit. Impedance was characterised using two modes of broad bandwidth current, frequency sweep (black) and broad bandwidth noise (dashed).
Both types of broad bandwidth excitation resulted in resolution of the complex impedance spectrum and were comparable to those predicted mathematically for the linear RC network. We applied the method to real electrodes placed on or in the skin, and to cuff electrodes implanted around peripheral nerve. A typical example of an impedance spectrum from a cuff electrode implanted in an acute rabbit preparation is above in figure 2.

The impedance spectrums characterised by the frequency sweep were generally cleaner than those characterised by broad bandwidth noise. Broad bandwidth noise characterised impedances also showed greater phase error, especially at frequencies approaching 10 kHz.

DISCUSSION

Transfer function estimation using pointwise division of Fourier coefficients is a promising method for quickly determining the complex impedance of implanted electrodes. The principle advantage of the method is that a more continuous impedance spectrum can be generated, consisting of hundreds or thousands of frequency points based on a single 20-30 second sampling. We found that, the shape and features of the theoretical impedance of the linear components and the complex electrode impedance from literature based on multiple single frequency measurements were generally well reproduced using this method.

The successful implementation of the method hinges on the use of broadband excitation to ensure that there is sufficient energy in the excitation waveform at all frequencies within the range of the impedance characterisation. We tested two different modes of this broadband excitation, frequency sweep and broadband noise, and found that frequency sweep excitation resulted in cleaner and faster characterisation of the complex impedance spectrum. There was considerable error and chatter in the impedance spectra derived based on broad bandwidth noise excitation. Although its performance was significantly poorer than the frequency sweep excitation mode, broadband noise excitation has one significant advantage, it is simple to generate, and thus can be easily implemented into hardware. The accuracy of the transfer function estimation can be improved by increasing the duration of the sampling period or decreasing the frequency range of the spectrum to be characterised to increase the number of spectra averaged using Welch’s method of spectral averaging.

The basic rationale for exploring complex impedance spectrum was to determine whether it is possible to evaluate the condition of the electrode/tissue interface and that of the implanted tissue based on a simple non-invasive measurement. Looking towards future work, we intend to take this method and test it in the chronic animal model to determine whether the effects seen by Williams et al with cortical electrodes have similar correlates with peripheral nerve electrodes. It remains to be seen if less selective peripheral nerve electrodes will be able to resolve the local effects seen with intracortical electrode arrays. Nonetheless, the measurement of the complex impedance spectrum offers the possibility of parametric value estimation of components in a mathematical model of the electrode and surrounding tissue.

REFERENCES
