THE ELECTRICAL BEHAVIOR OF A CUFF ELECTRODE IMPLANTED ON A HUMAN OPTIC NERVE

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Abstract

The well known complex behavior of electrode interfaces does not lend itself to a manageable formulation of tension-current characteristics. Empirical but efficient solutions are proposed here on the basis of experimental data obtained in the case of a cuff electrode chronically implanted around the optic nerve of a human volunteer.

A relatively simple mathematical expression is found to provide very accurate representation of the potential generated across the electrodes by a rectangular current pulse. In this case, the time and current dependent electrode resistance can be described in terms of four parameters. This model can only roughly be approximated by a passive electric circuit including one capacitor and two resistors, but such a simple output load model is sometimes required for stimulator evaluation.

Introduction

Stimulation of the right optic nerve of a blind human volunteer has now been applied for several years in the frame of the 'Microsystems based Visual Prosthesis', or 'MiViP' project [1]. Within that frame, the electrode voltage-to-current relationship is of course an essential piece of working information concerning the stimulator as well as the implanted electrodes.

The complex wave shapes of the potentials observed across the connections when passing a known current through a pair of electrodes are however difficult to handle. Several electric models of the electrode interface and tissue impedance have been described [2, 3] and a relatively simple version is given in Fig. 1. In this circuit, R1 and R5 represent non linear, current dependent, resistors (Warburg impedance). In the stimulation loop, these components see current I with an opposite polarity for each of them. This means that even working with a supposedly identical pair of electrode contacts would result in dissimilar impedances and the schematic cannot be simplified by considering two identical halves.

The purpose of the work presented here is thus to develop an efficient description of the electric behavior of an electrode pair, simple enough for all parameters to be estimated in the context of functional implants.

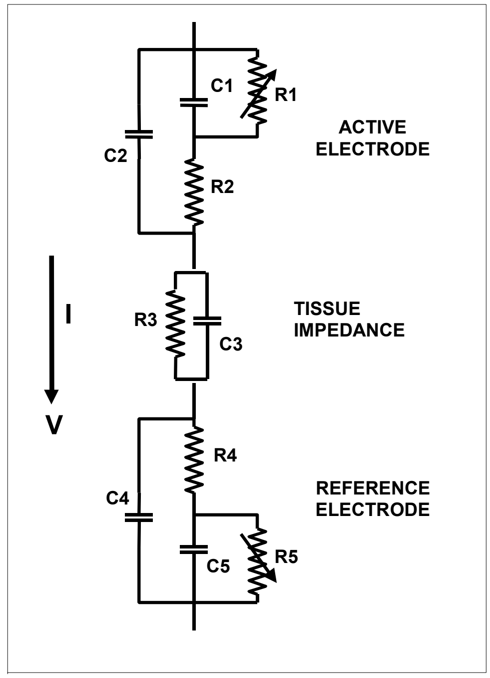

Figure 1: *A simplified equivalent electric circuit for electrode and body tissue impedance.*

Methods

1. The procedure

The data are obtained in the frame of the MiViP project which fully complies with the Declaration of Helsinki, and was approved by the Ethics committee of the School of medicine and University Hospital of the University of Louvain [1].

The measurement currents used are biphasic rectangular pulses mainly in the range applied to generate functional phosphenes. This includes first pulse durations of 21, 42, 105, 400 and 10000 (not used for phosphene generation) µs and amplitudes of 10, 100, 1000 and 3000 µA. Only short pulses were combined with the largest current settings in order to keep the charges injected below 100 nC (or 50µC/cm²). The charge recovery phase is about five times longer and smaller in amplitude compared to the first pulse.

The implanted self-sizing spiral cuff electrode carries four 0.2 mm² platinum contacts. The monopolar montages use each one of the contacts as a cathode and a skin electrode made of a 4 x 50 x0.1 mm pure silver foil as reference anode. This anode was placed over the left mastoid after careful skin preparation with alcohol and using Lectron II ® from Pharmaceutical Innovations, inc., as a conductivity gel. All the results used here were obtained during a single session, thus without changing the skin reference electrode. Bipolar recordings simply refer to those cases where the current is passed between any combination of two contacts within the cuff.

A custom-build high precision current controlled stimulator delivers the required pulses with a negligible distortion ratio lower than 10^{-6}. The current pulse shape is represented as trace I in Fig. 2. The electrode potential is fed to a Tektronix TDS 420A oscilloscope through a ADA400A preamplifier (1 MΩ ± 2% input impedance and DC - 1 MHz band-pass, DC gain accuracy ± 2%). The traces obtained are recorded for further computer processing.

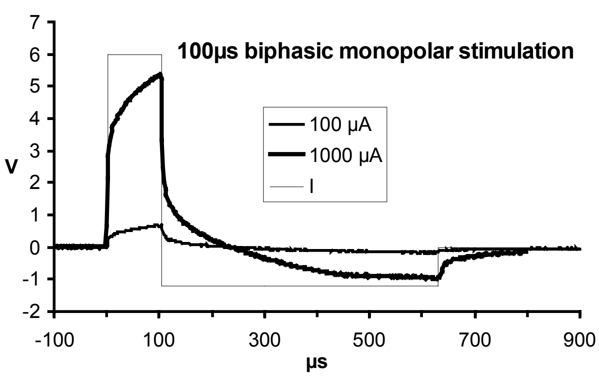

Figure 2. *Typical examples of voltage recordings to 100 µA and 1000 µA pulses. The thin trace shows the shape of a stimulation pulse with a 100 µs first phase that would have an amplitude of 100 or 1000 µA for the corresponding voltage traces.*

2. The model

Considering the shape of the tension traces of Fig.2 and the descriptive equations applying to the circuitry of Fig. 1, several possible empirical mathematical model involving a function of I and a function of t were tested. Finally, the following equation was selected on the basis of a best fit with the experimental data:

$$V = I \bullet [P_0 \bullet Ln(t + P_1) + P_2 \bullet (Ln(I + P_3)]$$

The four parameters P0…P3 defined by this model were computed using a Levenberg-Marquadt fitting procedure minimizing an error function [4]. Calculations were only performed on the data points corresponding to the first pulse of the stimulus. All units are mV for potentials, µA for currents, µs for time with zero value at the onset of the first pulse.

Results

The average results are given in table I for the four monopolar derivations and the twelve possible bipolar montages.

	Monopolar	Bipolar
P_0	1.84	2.49
P_1	71.8	62.4
P_2	-0.67	-1.03
P_3	19.6	12.8
Signal variance	3.87	3.79
Sum SQR error	0.058	0.063
r^2	0.986	0.984

Table I.

There was a variability of the parameter values corresponding to different electrodes but a very good fit to the experimental data as expressed by the r² values. This table also shows that there are only relatively small differences between the parameters for the monopolar and the bipolar montages. Another point illustrated in the table is that the parameters P_2 and P_3 involving the dependence on I are clearly smaller than their time function counterparts.

For practical purposes such as the construction of a dummy output load for stimulator testing, the model still has to be translated in the form of an relatively simple electric circuit. Considering separately the situation for selected current levels while accepting that expression $Ln(t+P_1)$ can be very roughly approximated by a function of the form $(1-e^{-kt})$ then, the complete circuit of figure 1 can be replaced by the simple load of Fig. 3.

Table II was constructed by calculating the value of the various components of the circuit in figure 3 on the basis of the monopolar and bipolar mathematical models. At time t=0, the capacitor has zero impedance and the load corresponds to R1. By approximation, t=10000 has been considered as the time where conductance through C would be negligible, yielding a global impedance equal to R1+R2. Finally, the time constant was calculated as the time at which the impedance represented by C and R2 becomes equal to R2.(1-1/e). The value of C is then extracted from this time constant. These results are presented in table II. Values of R1 are given for three levels of current. Their range for I between 0 and 1 mA mainly represent the working conditions of the cuff electrode around the optic nerve.

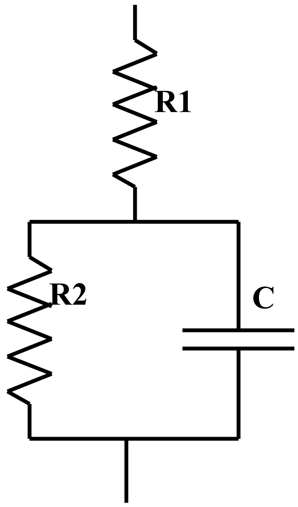

Figure 3. *This figure represents a global electrical equivalent load as seen from the stimulator output.*

The parameters have been computed for the monopolar as well as the bipolar montage, yielding a larger value of R2, a smaller capacitor and more current dependence of R1 in the bipolar case.

	R1 I = 0	R1 I=1000µA	R1 I=3000µA	R2	C (nF)
M	5.9 kΩ	3.3 kΩ	2.5 kΩ	9.1 kΩ	275 nF
B	7.7 kΩ	3.1 kΩ	2.0 kΩ	12.7 kΩ	186 nF

Table II

Discussion

The wave shapes observed here are in keeping with well known data from the literature [2, 3]. The proposed mathematical model very accurately describes the tension-current relationship at the connections of the implanted cuff electrode. In addition, an electric circuit is described that approximates the behavior of the load connected to the stimulator. Despite the gross approximations necessary to arrive at such a simple circuit, it is still necessary to represent R1 at several current levels because of the dependence on this variable. Changes with time are even more important but reasonably taken into account by the introduction of a time constant.

The impedance values presented in this work were obtained 2.5 years after implantation of the cuff electrode around the optic nerve. They compare very well with much cruder estimations performed earlier (between 3.5 and 8 kOhm at the end of 100µs pulses of 300 to 990 µA one week after implantation and repeated on several occasions since).

A surprising but constant finding is that the skin electrode, with gigantic proportions compared to the implanted contacts, does not introduce a major difference in the overall loop impedance. As can be expected from it's larger size, the capacitance is more important and the series resistance (R2) is smaller for the skin electrode than for the implanted contacts. It is also worth noting that the current dependent resistance is much more sensitive in the case of the small implanted platinum contacts than in the case of the skin electrode.

Variability of the estimated parameters deserves further study with repeated measurements in similar settings but also generalization to other tissues and materials. As shown in table II, the current polarity can play a major role and the sensitivity to current is different from contact to contact. Because of the electro-chemical nature of the mechanisms underlying these changes, it is also likely that the history of the currents to which one contact has been exposed previously significantly modulates the subsequent electrical behavior.

References

[1] Veraart C, Raftopoulos C, Mortimer JT, Delbeke J, Pins D, Michaux G, Vanlierde A, Parrini S, Wanet-Defalque M-C. (1998) Visual sensations produced by optic nerve stimulation using an implanted self-sizing spiral cuff electrode. Brain Res., 813[1]: 181-186.

[2] Mortimer J.T., (1981) Motor prostheses, In: Handbook of physiology, section 1: The nervous system – Volume II Motor Control. Chapter 5. Brookhart J.B., Mountcastle V.B. (section eds), Brooks V.B. (volume ed.), American Physiology Society, Bethesda, MD. p 155-187

[3] Carim H.M. (1988) Bioelectrodes. In: Encyclopedia of medical devices and instrumentation Webster J.G. ed. John Wiley & Sons New York, Vol. 1; p195-226

[4] Delbeke J, Pins D, Parrini S, Michaux G, Wanet-Defalque M-C, Veraart C. (2001) Electrical Stimulation of Anterior Visual Pathways in Retinitis Pigmentosa. Invest. Ophthalmol. Vis. Sci., 42: 291-297.

Acknowledgments: Support: CEU 'Esprit' grant # 22 527 and FMSR grant # 3.4584.98.