

THE IMPEDANCE PROPERTIES OF NEEDLE ELECTRODES
FOR
ELECTROMYOGRAPHY

by
Victor Pollak
University of Saskatchewan

Abstract

Needle electrodes are extensively used in electromyography. The impedance properties of these electrodes are an important parameter for the design of the associated recording equipment and for the interpretation of the results obtained. It was therefore decided to investigate theoretically the factors which determine the impedance of the electrode for a.c. signals and its frequency dependence. The conclusions obtained were then verified experimentally. Though the primary objective was electromyography, it is assumed that the results may prove useful for other applications e.g. metal microelectrodes, pacemaker electrodes, etc.

The interface between electrode metal and tissue was simulated by a diffusion equation as commonly used to describe the characteristics of a n-p semiconductor junction. This equation in turn can be modelled by the input impedance of an electric RC-transmission line with the static capacitance of the double layer at the electrode surface in parallel and the spreading resistance of the tissue in series. The magnitude of the impedance turns out to be dependent upon the electrode material and its surface properties as well as upon the effective contact area between electrode and tissue.

The impedance properties of the pick-up electrodes are of considerable importance not only for the design of the input circuit of electromyographic equipment, but also for the interpretation of some of the results obtained. In most cases it is the small exposed area at the tip of the active electrode (or electrodes in the case of the bipolar needle), which determines the overall impedance of the pick-up circuit. The physico-chemical mechanism responsible for this impedance shall therefore, be now investigated.

When a metal electrode is inserted into an electrolyte solution, there is a tendency for metal atoms at the electrode surface to become dissolved in the liquid as positively charged cations. Their loss leaves the metal lattice with an excess of electrons, which gives the metal a negative charge. This charge interacts with the dissolved ions, attracting them back to the surface of the metal; at the same time the electrons also migrate to the surface forming there together with metal ions an electrically charged double layer.

The situation can be described by the simplified energy diagram in Fig. 1. At a regular lattice position the metal atoms have a potential energy Q_0 . If dissolved in the liquid their potential

energy is Q_2 . Between metal and liquid there is an energy crest Q_1 . An ion migrating from the metal to the liquid has to have a kinetic energy larger than $Q_1 - Q_0$. For migration in the opposite direction the minimum energy required is $Q_1 - Q_2$. In the absence of an external electric field this energy has to come from the thermal energy of the system. As long as $Q_1 - Q_2 < Q_0 - Q_2$, more ions will leave the metal lattice than return to it. However, the potential due to the electric charge created by the free electrons left behind increases the energy difference $Q_1 - Q_0$ until it becomes equal to $Q_1 - Q_2$. Equilibrium is then reached with an equal rate of flow of metal ions in both directions.

From classical thermodynamics it is known, that from a set of particles with average kinetic energy kT (where T is the temperature and k Boltzmann's constant) a fraction $e^{-Q/kT}$ is able to overcome an energy barrier of height Q . For our purposes it is convenient to express energy in electron-volts. Doing this we obtain a barrier voltage V_q and a temperature voltage V_T , which at room temperature is approximately 26mV. The fraction above determines the free ions density in contact with electrode surface. Each ion carries however a charge $z \cdot \eta_0$, where z is the valence of the ions and η_0 the electron charge. We therefore arrive at a free charge density q_0 proportional to e^{-zV_q/V_T} . Part of this free charge moves continuously across double layer in both direction, producing an "exchange current". This current is one of the key parameters which determines the general impedance level of the electrode.

The energy barrier between metal and electrolyte is typically of the order of electron volts, much higher than the temperature voltage. Consequently we might expect very low values of free charge density and extremely high impedance levels. Fortunately however there are usually defects in the metal lattice, where barrier voltage is low and consequently the free charge density increases many times.

The principal mechanism moving ions across the boundary is diffusion. This holds also when an external field is applied. To find the voltage-current dependency, that is the impedance, we can now apply the well known diffusion equation in its one-dimensional form to the charge density $q(x, z)$:

$$\frac{\partial^2 q(x, t)}{\partial x^2} = \frac{1}{D} \left[-\frac{\partial q(x, t)}{\partial t} + \frac{q(x, t)}{\tau} \right] \quad (1)$$

Here τ is the life time of the charge carriers and D a temperature dependent coefficient called diffusivity. It determines the charge flow due to a unity gradient of charge. With its help we obtain the density $j(x, t)$ of the diffusion current equal to $-D \times \partial q(x, t) / \partial x$. The second term on the right hand side of equation (1) takes care of the loss of charge carriers due to neutralization of the ions.

Equation (1) can now be compared term by term

with the familiar equation for the voltage $v(x, t)$ and the current $i(x, t)$ of an electric transmission line with longitudinal resistance R , a shunt capacity C and shunt conductance G , all per unit of length. Doing this we obtain the correspondences:

$$q(x, t) \rightarrow v(x, t); j(x, t) \rightarrow i(x, t); 1/D \rightarrow R; 1/\tau \rightarrow G; 1 \rightarrow C$$

The average distance an ion diffuses away from the electrode is in our case always small against the electrode spacing. In our transmission line model this amounts to infinite length.

When an external-voltage $V_e(t)$ is applied between electrode and electrolyte, the number of charge carriers able to climb the energy barrier becomes proportional to $e^{-zV_q/V_T} \cdot e^{-zV_e(t)/V_T}$. If V_e is small enough, a linear approximation to the second term can be used. Remembering that the first term determines the charge density q_0 at the interface we obtain a change in this value due to V_e :

$$\Delta q(0, t) \approx q_0 \cdot \frac{zV_e(t)}{V_T} \dots (2)$$

This relation gives us the necessary boundary condition for solving equation (1). We need the solution expressed in terms of frequency. Using the well known expression for the input impedance of a RC-transmission line we obtain by analogy for the electrode impedance per unit surface area:

$$z_e = \frac{V_e(t)}{j(0, t)} = \frac{\Delta q(0, t)}{\Delta j(0, t)} \cdot \frac{V_T}{z \cdot q_0} = \frac{V_T}{z \cdot q_0} \frac{\tau}{D(1+j\omega\tau)} \dots (3)$$

Relation (3) can be modelled by the input impedance of a RC-transmission line of infinite length. A more detailed analysis shows, that two further elements have to be added: a series resistance R_s at the input, which represents the spreading resistance of the medium surrounding the tip of the electrode. It varies inversely with the tip diameter of the electrode. The second element to be added is a shunt capacity C_L at the input of the transmission line, which represents the static capacity of the double layer. In electromyographic applications it can usually be neglected.

From the equivalent diagram described the following conclusions can be reached: At very low and very high frequencies the electrode impedance is almost purely resistive and therefore constant. In the intermediate range it decreases with $1/\omega$, corresponding to a slope of 3dB per octave on a logarithmic scale and to a phase angle of approximately $\pi/4$.

For many purposes a low level of electrode impedance is strongly desirable. q_0 is however dependent upon the properties of the electrode material. Its proper choice can therefore strongly influence the impedance characteristics. (Fig. 2). A high value of q_0 and therefore of exchange current density, a low valence number, short life time and high mobility of the ions are

desirable features of the electrode material.

The impedance determined by equation (3) refers to unit surface area. Increasing the effective contact area of the electrode by mechanical, chemical or electrical is therefore highly efficient in reducing the electrode impedance. In electromyography electrolytic etching is commonly employed. To produce this effect the electrode is inserted into a weak electrolyte. A voltage is applied between electrode and electrolyte and increased until gas bubbles begin to appear. At this level the voltage is maintained for about 1 minute. The result is a sharp decrease in impedance as shown in Fig. 1. The effect is however not lasting and the procedure has to be repeated from time to time. An other procedure common in microelectrode techniques is "platinizing" the electrode metal in a bath of "Kohlrausch's" solution, the principal component of which $PtCl_2$. It results in a spongy layer of platinum black on the substrate metal.

This procedure has to be repeated still more frequently, since the layer of platinum black has only little mechanical strength. It should be noted, that neither of these measures affects the spreading resistance R_s .

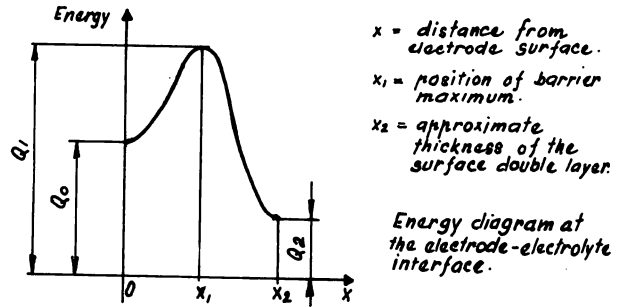
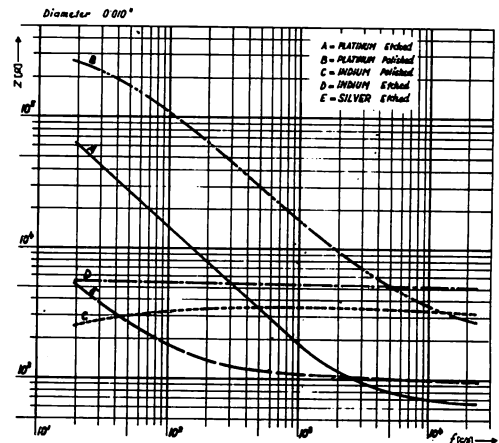


Figure 1.



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Reference: D.A. Robinson, "The Electrical Properties of metal Microelectrodes, Proc. I.E.E.E. Vol. 56, 1968, No. 6, pp. 1065-1071.