Electrical Bioimpedance Cerebral Monitoring

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INTRODUCTION

Electrical Bioimpedance (EBI) is now a mature technology in medicine, with applications in clinical investigations, physiological research, and medical diagnosis (Schwan, 1999). The first monitoring application of bioimpedance techniques, *impedance cardiography,* date back to 1940. Since then, bioimpedance measurements have been used in several medical applications, from lung function monitoring and body composition, to skin cancer detection. A complete historical review is available in Malmivuo and Plonsey (1995). A medical imaging modality based on bioimpedance, *Electrical Impedance Tomography* (EIT) has also been developed (Bayford, 2006).

EBI has been used to study the effect in the brain of spreading depression, seizure activity, asphyxia and cardiac arrest since 1950s and 1960s (Ochs & Van Harreveld, 1956), but the most important activities in electrical cerebral bioimpedance research has been during the last 20 years (Holder, 1987; Holder & Gardner-Medwin, 1988). Examples of areas of study are *brain ischemia*, *spreading depression*, *epilepsy*, *brain function monitoring*, *perinatal asphyxia*, *monitoring of blood flow, and stroke*.

BACKGROUND

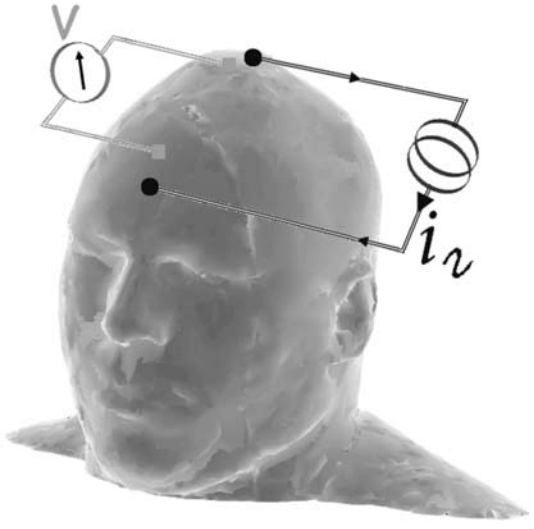
The basic functional units of an EBI measurement system for cerebral monitoring are the following: an electric current generator, a voltage meter, the surface electrodes for current injection and voltage pick up as well as the connecting electrical leads. The injected current causes a voltage drop in the tissue that is sensed and the measured bioimpedance is calculated from the resulting quotient from voltage over current, know as Ohm's Law. See Figure 1 and Equation 1.

$$\boldsymbol{Z}(\omega) = \frac{\boldsymbol{V}(\omega)}{\boldsymbol{I}(\omega)} \quad (1)$$

An important feature of the application of EBI for cerebral monitoring is that it is applicable in some of the situations where brain is particularly at risk as well as for long-term monitoring situations where available imaging techniques: *MRI, CT-scan* are not suitable (*e.g., during an ongoing cardiopulmonary by-pass operation, in intensive care, for acute stroke assessment in ambulances*).

Other features of bioimpedance technology are that it is harmless for the patient, portable and very affordable in comparison with other monitoring techniques already in used. These specific features place EBI as the technology of choice to fill the need for brain monitoring in the medical scenarios mentioned above and several others.

Figure 1. Functional diagram of a measurement system for electrical bioimpedance cerebral monitoring



Electrical Properties of Biomaterials and Bioimpedance

Biological material, tissue, and cells have electrical properties (conductivity σ and permittivity ε) that allow electrical current to flow in the presence of an electric field (Cole, 1968). These electrical properties depend of the constitutive elements and structure of tissue; therefore, changes in structure or biochemical composition modify the electrical properties, σ and ε, of the tissue, and consequently the electrical impedance changes.

Every type of tissue and body fluids in the human body exhibits specific values of conductivity and permittivity that are frequency dependent. Therefore, each tissue can be characterized by its particular electrical impedance spectrum, and measurements of electrical impedance can be used to differentiate between tissues or to assess the state of the tissue. The most complete compilation of the dielectric properties of biological tissues is found in (Gabriel, 1996).

Electrical Impedance Tomography

EIT exploits the fact that the electrical properties differ between tissue types to create an image representing the conductivity distribution of a volume conductor. Despite its name, EIT does not reconstruct and object slice by slice, because electrical current cannot be confine in to a plane; instead, the current will flow through the whole volume conductor following the gradient of the electrical field.

As several conductivity distributions may provide the same voltage boundary detected by the sensing electrodes, reconstruction of the impedance image requires that some assumptions are made, and also that a model is used for fitting the voltage boundary data.

There are two methods for EIT imaging: absolute and difference imaging. The first one, also known as static method, obtains a conductivity image from a set of impedance measurements. The difference imaging method uses a set of two measurements taken at two different times to create a conductivity image of the differences. This method is used for dynamic studies, for monitoring changes in the tissue.

EIT imaging exhibits a poor spatial resolution as compared to other imaging techniques but the time resolution, in the order of microseconds, is unique for EIT. Affordable, portable, and noninvasive are other exclusive features to EIT within brain imaging monitoring. For a deep understanding of EIT, see a recent review (Bayford, 2006).

Electrical Impedance Spectroscopy Analysis

One straight-forward effect of the frequency dependency of electrical properties of tissue is the effect of the cellular membrane. Figure 2 shows the influence of the frequency on the current path lines. The capacitive effect of the membrane contributes to the electrical properties of tissue and depends of many factors: the number of cells, the size of the cells, the thickness of the cell membranes, type of cells, and so on.

Because the plasma membranes of the tissue cells act as a capacitive element, most of a direct current (DC) in biological tissue, flows through the extracellular space (*e.g., interstitial fluid, plasma, and so on*). Hence, the impedance at DC is mainly determined by the conductivity of the extracellular fluid, the available surface to the electrical field for the charges to flow through, and the length of the propagation path. See Figure 2 and Equation 2. At higher frequencies the capacitive effect shunts the electrical current, allowing the electrical current to propagate also via the intracellular space and the tissue conductivity can be modelled as in Equation 3.

$$\boldsymbol{g_{DC}} = \sigma_e \frac{2(1-\boldsymbol{f})}{(2+\boldsymbol{f})} \tag{2}$$

$$\boldsymbol{g} = \sigma_e \frac{2(1-\boldsymbol{f})\ \sigma_e + (1+2\boldsymbol{f})\left(\frac{\sigma_i\ (\sigma_m + i\omega \boldsymbol{C}_m)a}{\sigma_i + (\sigma_m + i\omega \boldsymbol{C}_m)a}\right)}{(2+\boldsymbol{f})\ \sigma_e + (1-\boldsymbol{f})\left(\frac{\sigma_i\ (\sigma_m + i\omega \boldsymbol{C}_m)a}{\sigma_i + (\sigma_m + i\omega \boldsymbol{C}_m)a}\right)} \tag{3}$$

Equations legend: $\boldsymbol{g}$ is the complex conductivity of tissue, $\boldsymbol{\sigma_e}$ is conductivity of the extracellular fluid, S×m^{-1}, $\boldsymbol{\sigma_i}$ is conductivity of the intracellular fluid S×m^{-1}, $\boldsymbol{\sigma}_{\mathrm{m}}$ is the membrane conductivity, S×m^{-1}, $\boldsymbol{c_m}$ is the surface membrane capacity, Farads×m^{-2}, ω is the angular frequency, radians×s^{-1}, $\boldsymbol{i}$ is the imaginary number √-1, $\boldsymbol{a}$ is the cell radius and $\boldsymbol{f}$ is the volume fraction of concentration of cells.