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General Review

Review on Biomedical Techniques for Imaging Electrical Impedance

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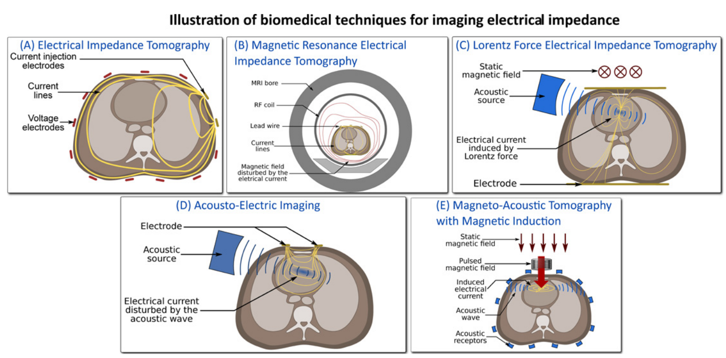
Highlights

- Electrical impedance of a medium helps to predict the behavior of electrical currents.
- Combining electrical current, magnetic fields, and acoustics have led to new imaging techniques.
- It is hard to predict at this stage the potential biomedical applications of these techniques.

Graphical abstract



Abstract

Electrical impedance of a medium helps to predict the behavior of electrical currents in a medium. Electrical impedance refers indeed to the "difficulty", for an electrical current, to spread through the medium. While the first impedance measurements were focused on cardiovascular parameters, techniques are now being applied to the whole body, as electrical impedance present important variations through the human body and could then offer a new source of contrast.

Combining electrical current, magnetic fields, and acoustics in various ways have led to interesting techniques to image this parameter: Electrical Impedance Tomography, Magnetic Resonance Electrical Impedance Tomography, Acousto-Electric Imaging, Lorentz Force Electrical Impedance Tomography and Magneto-Acoustic Tomography. These techniques are detailed in this review.

1. The electrical properties of a medium

Effects of electrical currents on biological tissues have been observed since the end of the 18th century, with the observation of frog muscular movements due to electricity by Luigi Galvani.

The electrical properties of a medium can be described by its global impedance Z, linking voltage V and intensity I with Ohm's law $U = ZI$, or locally by its impeditivity: $\mathbf{E}(\mathbf{r}, t) = \rho(\mathbf{r})\mathbf{j}(\mathbf{r}, t)$, where $\mathbf{E}$ is the electric field in a given point $\mathbf{r}$ at a time t, $\mathbf{j}$ the current density at this point and time and ρ the local

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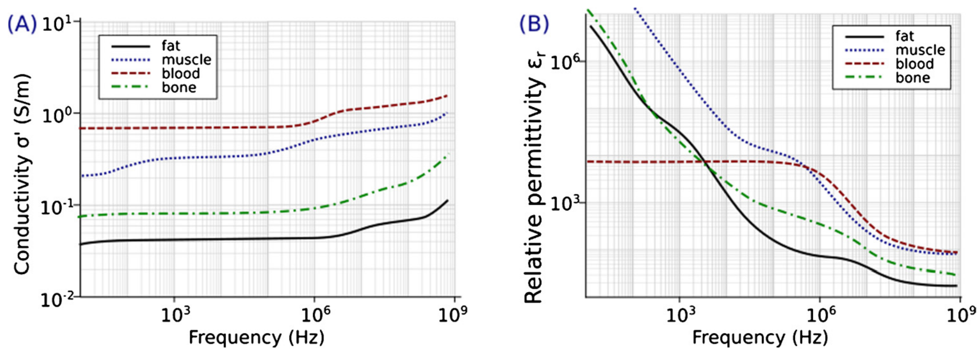

Fig. 1. Variation of the electrical conductivity (A) and relative permittivity (B) of fat, blood, muscle and bone as a function of frequency (adapted from [4]).

impeditivity.[1] But for electrical impedance imaging techniques, authors prefer often to use the admittivity σ, defined as $\mathbf{j}(\mathbf{r},t) = \sigma(\mathbf{r})\mathbf{E}(\mathbf{r},t)$, with the Siemens per meter ($S.m^{-1}$) as unit.

The admittivity is written as the sum of a real and imaginary part according to the relation $\sigma = \sigma' + i\sigma''$, where σ' is the electrical conductivity and σ'' the susceptivity. Admittivity and electrical conductivity are often mixed up when imaginary part plays a minor role.

The conductivity σ' represents the loss of current due to the displacement of the free and bound charged particles. This quantity can be separated into the sum of two components, σ'_s which represents the resistive losses in the medium (resistance to free particles motion) and σ'_d which represents the dielectric losses (resistance to the movement of bound particles).

The susceptivity σ'' represents the polarizability of the material, and therefore its ability to store energy in the form of an electric field. Several polarization mechanisms exist, such as orientational polarization of rigid dipole molecules, ionic polarization, deformation of the electron cloud of atoms [1]. Each type of polarization has a maximum response to a defined electric field frequency: at this frequency, a resonance mechanism leads to an absorption of energy in the medium. The relative permittivity ϵ_r can be defined as the susceptivity divided by the pulsation ω: $\epsilon_r = \frac{\sigma''}{\epsilon_0 \omega}$., where ε_0 is the dielectric permittivity of the void. This magnitude is more often used because it has generally a smaller amplitude variation than σ''.

More details can be found in [1].

1.1. Electrical properties of biological tissues

From the electromagnetic point of view, biological tissues are complex media, quite different from other materials.

Biological tissues electrical impedance is mainly set by the movement of ions. Generally speaking, tissues which have a low concentration of ions, such as adipose tissues, will be less conductive than ones with a high concentration, such as muscles.

As an example, the conductivity and the relative permittivity of four biological media (muscle, blood, fat, bone) are shown in Fig. 1-(A) and -(B): at 1 kHz, fat, muscle, blood and bone have respectively a conductivity of .04 $S.m^{-1}$, .08 $S.m^{-1}$, 0.3 $S.m^{-1}$ and 0.7 $S.m^{-1}$, and a relative permittivity of 7.10^3, 20.10^3, 30.10^3 and 700.10^3.

Detailed measurements in many organs can be found in [2, 3], considered as references.

1.2. Healthy tissues and tumor tissues

Several studies showed tumor tissues with different electrical properties from healthy tissues. For example, a study from Haemmerich et al. showed that at 1 MHz, the electrical conductivity of hepatic tumors was 15% higher than the one of healthy tissue (5.23 ± 0.82 $S.m^{-1}$ vs 4.61 ± 0.42 $S.m^{-1}$) [5]. According to the authors, the probable reason of this change is the necrosis within the tumor and associated cell membranes breakdown. Although further measurements are needed to assess the clinical interest of measuring electrical conductivity, this suggests that it might have an interest to help diagnose tumorous tissues. Measurements made at different frequencies could also lead to more information, for example in the breast [6] or for the prostate [7].

1.3. Temperature dependence

The temperature also significantly affects the electrical conductivity of the tissues. F. Duck showed, for example, that at 100 kHz, the electrical conductivity of a piece of muscle heated between 20 and 40 °C has an average increase of 2.1% per degree [8]. Similar values have been found for many biological tissues. Electrical conductivity could consequently be used to indirectly monitor temperature changes over time in a tissue [9], for example during thermal ablation by high intensity focused ultrasound.

2. Electrical impedance imaging techniques

Although the electrical properties of biological tissues have been intensely studied, only a few methods exist for making non-invasive images of electrical conductivity. In medical imaging, the oldest and most developed method is the Electrical Impedance Tomography. It is currently used in clinics for some specific applications such as monitoring of lungs ventilation.

[1] if ρ is complex, it can be separated as the sum of a real part, the resistivity, and an imaginary part, the reactivity.