Mutual localization of electrode pairs in a 4-electrode measuring system

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Abstract. The purpose of this study was to examine the transformation of a 2-electrode system into a 4-electrode system by gradually removing the current carrying (CC) electrode pair from the stationary signal pick-up (PU) pair. Both a Finite Element Method (FEM) analysis on a homogeneous tissue model and in-vivo measurements were used. We found that the general transfer impedance dependence on CC electrode distance was similar for the two methods. With the same excitation current the transfer impedance of a 4-electrode system may be measured with less than 1/10 of the signal amplitude obtained with a 2-electrode system. Also the transfer impedance spectra changed character. The admittance characteristic frequency of the alpha dispersions increased from 32 Hz to 160 Hz and beta dispersions decreased from 100 kHz to 13 kHz with increasing distance.

1. Introduction

A major problem in bioimpedance work has been electrode polarization. This was discussed in detail by Schwan [1]. He listed four different solutions and one of these was the 4-electrode technique. However, these solutions were used for in-vitro work usually with the examined tissue or suspension in a tube where the current flow direction was well defined and parallel to the tube axis. Measuring the impedance of a multilayered tissue volume with current spread from the current carrying (CC) electrodes implies additional problems not treated by Schwan. One problem is the complicated electrode sensitivity distribution (sensitivity field) [2]. Sensitivity S is a factor determining the contribution of a voxel with local resistivity $\rho$ to the total measured transfer resistance.

$$S = J'_\text{reci} \cdot J'_\text{cc} \quad [1/m^4]$$

$J'_\text{reci}$ is the current density vector with 1 ampere excitation applied to the pick up (PU) electrode pair (reciprocal excitation). $J'_\text{cc}$ is the current density vector with 1 ampere excitation applied to the CC electrode pair. S is the vector dot product in a small voxel $dv$, and $\rho S$ is the impedance volume density [$\Omega/m^3$]. The transfer resistance $R$ is:

$$R = \iiint \rho S dv \quad [\Omega]$$

The purpose of this study was to examine the transformation of a 2-electrode system into a 4-electrode system by gradually removing the CC electrode pair from the PU pair by using both a Finite Element Method (FEM) analysis on a homogeneous tissue model as well as in-vivo measurements.
2 FEM analysis

The FEM analysis was carried out by modeling a “human tissue box” with our desired electrode configuration in COMSOL Multiphysics (CM) version 3.5. 4 disc electrodes were located in-line at the centre of the surface of the box, and they were modeled with a conductivity of $6 \times 10^7$ S/m corresponding to copper. The two PU electrodes were at fixed center-to-center distance of 6 cm, whereas the distance between the PU pair and the CC pair was gradually increased from 6 cm (i.e. a two-electrode system) up to 150 cm. The resistance was calculated as a function of distance between the CC electrodes.

The measuring volume, “the human tissue box” with dimensions 0.5x0.5x1.5 m$^3$ was assumed to be homogeneous and with a conductivity of 1 S/m. All the outer surfaces of the volume were given the conditions $\mathbf{n} \cdot \mathbf{J} = 0$. At the frequencies of interest ($< 1$ MHz) the relative permittivity was set to 1 for simplicity. Even if we calculate resistance we also call the parameter impedance $Z=R+jX$ with $X \approx 0$.

One result of the FEM simulations is given in figure 1, showing the impedance as a function of the distance between the CC electrodes. The two smallest CC distances correspond to a configuration where the CC and PU electrodes are physically in contact. The first point represents a complete overlap of the two sets of electrodes, which effectively is a two-electrode system, whereas the second point is the limit where the CC and PU are just in physical contact. All remaining values represent a 4-electrode configuration. We note the sudden drop in impedance as the system suddenly transforms from a two – and into a four-electrode setup. Two of the configurations studied in the in vivo measurements are highlighted in figure 1.

Resistance of a disk in a homogenous medium is $R=1/(4\pi\sigma)$, which in our case is about 19 ohm, when $a$ is the disc electrode radius 1.25 cm. With two discs at a center-center distance of 6 cm they must be expected to disturb the current density fields from one another. A correction term must be included, and the resistance between the two discs is

$$R = \frac{\rho}{2\pi a} \left( 1 + \frac{a}{L} + \left( \frac{a}{L} \right)^2 + \ldots \right)^{-1}$$

With the PU electrodes 6 cm apart we end up with a resistance of 24.2 ohm. This corresponds quite well with the simulated resistance of 22.6 ohm in the case of a two-electrode setup.

3 In-vivo study

Method

The test person was sitting on a chair with a thigh-leg angle of 90 degrees. All 4 electrodes were solid gel disks with skin-gel contact radius 1.25 cm and contact area $A=4.9$ cm$^2$ (Tyco, Kendall, modell KittyCat 1050NPSM Small). The fixed PU electrode pair had a center to center distance of 6 cm along the
longitudinal axis of the thigh as shown at figure 2. The two CC electrodes were localized outside the PU pair at four different positions: a) foot-hand (>50 cm), b) knee-hip (≈20 cm), c) 5 cm and d) 1 cm rim-to-rim distance from the respective PU electrodes. Impedance spectra were measured with a Solartron 1260/1284 system. We used a measuring mode with constant excitation voltage creating a measuring current dependent on the impedance of the CC system. Because tissue impedance is frequency dependent also the measuring current was frequency dependent. With 1 V rms excitation voltage the measuring current was typically about 15 μA at the lowest frequencies, increasing to about 1 mA at the highest frequencies.

Quality control

The Bode plots of figure 3 showed positive phase at the highest frequencies. Phase polarity reversals at high frequencies are often found in 4-electrode systems [3]. We found that the positive phase was not dependent on measuring current level, and it is most likely due to self-induction. The lower the impedance level, the stronger the influence from the inductive impedance \( Z = \omega L \) where \( \omega = 2\pi f \) and \( L \) the inductance [henry] of the measuring circuit. The relative contribution is larger the lower the measured total impedance, in accordance with figure 3.

Bode diagrams were controlled with the Kramers-Kronig rule (falling impedance with increasing frequency shall correspond to negative phase angles). All results were found compatible with the Kramers-Kronig rule.

Reciprocity was controlled by swapping the PU and CC pairs to check that the same spectra were obtained. Reciprocity criteria were not met at the lowest frequencies when excitation voltages >1 V rms were used. All impedance spectra were therefore performed with 0.5 or 1 volt rms excitation.

In-vivo results

The PU pair impedance spectrum showed two dispersions with characteristic frequency \( f_c \) around 1 kHz and 100 kHz. The low frequency part of the spectrum was dominated by the SC impedance of the skin. The lowest impedance result was 340 ohm at 631 kHz, this is the 2-electrode driving point impedance [4] of our in-vivo measuring system.

The 4-electrode transfer impedance obtained with 1 cm distance between the PU and CC electrode pairs is shown on figure 3. The characteristic frequency of the alpha dispersions increased from 32 Hz to 160 Hz and beta dispersions decreased from 100 kHz to 13 kHz with increasing distance.

4 Discussion

In Table 1 the FEM calculated values valid for sigma 1 S/m has been multiplied with a factor of ten and therefore corresponds to a sigma of 0.1 S/m. The FEM
values and in-vivo results have similar general trends. A common finding is the abrupt drop in impedance when the two pairs no longer are in direct contact. For the in-vivo case the drop is to less than 1/10 of the 2-electrode value when the CC pair is remote. This means that the recorded signal amplitude also may drop to 1/10, and the signal to noise ratio get poor. This is often experienced in practice, and a usual remedy has been to increase the measuring current. The problem then is that the non-linear zone is easily entered with nobody taking notice. When working with 4-electrode systems it is therefore good practice to perform the reciprocity test to ensure that the measuring current level is sufficiently low.

Table 1 Impedance as a function of distance between PU an CC electrode pairs, FEM model results (sigma = 0,1 S/m) and in-vivo measurement results.

| system | ohm in-vivo | ohm FEM results x 10 | condition |
|--------|-------------|-----------------------|-----------|
| 2-el   | 340         | 226                   | CC and PU pairs concentric in contact |
| 2-el   | 215         | CC and PU pairs in rim-to-rim contact |
| 4-el   | 38,0        | 59                    | CC electrode rims 1 cm from PU rims |
| 4-el   | 18,1        | 20                    | CC electrode rims 5 cm from PU rims |
| 4-el   | 8,1         | 20                    | CC electrode rims 20 cm from PU rims |
| 4-el   | 7,8         | CC electrode rims >50 cm from PU rims |

The differences between the two methods found in Table 1 are due to many factors. The in-vivo results are from the thigh, which has a smaller volume than “the tissue box” where the current is spread out in a larger volume and the current density for a given current will be lower and therefore also the recorded PU signal and the calculated impedance. The in-vivo results are influenced by the long and small volume segments of tissue as well as the tissue complexity.

5 Conclusions
The general transfer impedance dependence on CC electrode distance was similar for the FEM model and the in-vivo results. With the same excitation current the transfer impedance of a 4 electrode system may be measured with less than 1/10 of the signal amplitude obtained with a 2-electrode system. Also the transfer impedance spectra changed character with increasing distance, e.g. the characteristic frequency of the Y-plot alpha dispersions increased from 32 Hz to 160 Hz and beta dispersions decreased from 100 kHz to 13 kHz.

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