Analysis of Body Segments using Bioimpedance Spectroscopy and Finite Element Method

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Abstract—Elderly people and geriatric patients often suffer from dehydration which can be diagnosed by bioimpedance spectroscopy (BIS). In this work, the capability of segmental BIS to reflect the total body composition is analyzed. Therefore, measurements of body segments have been simulated using the finite integration technique (FIT) and the results have been verified by measurements on subjects. We show that results obtained from segmental BIS measurements correlate with whole-body bioimpedance spectroscopy measurements. Furthermore, simulations of segmental BIS have been successfully accomplished and the simulation results show similar characteristics compared to measurements performed for reference.

I. INTRODUCTION

Since the beginning of the 20th century, a demographic change is observable in Europe which leads to a steadily aging society. Looking at Germany as an example, the average life expectancy of women is supposed to rise from 74.2 to 87.1 years between 1913 and 2035. Important factors are the continuous progress in medical technology and the decreasing birth rate of actually around 1.4 children per couple [1]. Hence, society will have to face more and more geriatric patients, which leads to additional costs and burdens on medical personnel. Thus, it is reasonable to establish methods to treat elderly people more cost-effectively and more easily by improving diagnostics for certain diseases that prevalently occur among elderly people.

One of these diseases is dehydration, which describes a water deficiency in the body. This deficiency is primarily caused by a lower thirst sensation and a disturbed hormone balance [2]. Also athletes can suffer from dehydration during physical exercise, which can lead to lifethreatening situations. The project NutriWear, funded by the German Federal Ministry of Education and Research (BMBF), aims at developing a wearable system to monitor the nutrition and hydration status based on intelligent textiles. What is more, the patient shall be monitored 24 hours per day [3]. Such a system can be used for preventive monitoring of dehydration.

Dehydration can be easily and cost-effectively diagnosed by bioimpedance spectroscopy (BIS). Currently, BIS is not commonly used as diagnostic method because it is not considered to be valid, even though there are a lot of studies implying the opposite [4]. One possible reason is that many processes in the human body during BIS are widely unknown.

One way to analyze where the current paths run, and which tissue contributes significantly to the measurement result, is to use computer simulations employing FIT [5].

In the following, correlations of segmental BIS and whole-body BIS measurements shall be analyzed and compared with simulations of segmental BIS measurements.

II. BIOIMPEDANCE SPECTROSCOPY

The basic idea of BIS is that each cell consists of a capacitive cell membrane, separating extracellular and intracellular space. When injecting an alternating current into a certain tissue, these membranes lead to a current flow between the cells through the extracellular water (ECW) at low frequencies. At high frequencies, the membranes are no barrier for the current so that it flows through all cells now as a function of ECW as well as intracellular water (ICW) (cf. fig. 1).

There are three major dispersion regions: $\alpha$ (mHz - kHz), $\beta$ (0.1 - 100 MHz) and $\gamma$ (0.1 - 100 GHz). The frequency range between 1 kHz and 10 MHz within the $\beta$ dispersion region is generally the most interesting one for diagnosis because physiological and pathophysiological processes lead to changes in body impedances with high dynamics in this range. The reason for this is polar proteins and organelles which behave like dipoles in the alternating field [6]. In addition, in this frequency region safety regulations permit higher alternating currents than in the frequency range below 1 kHz. Thus, the degree of measurement accuracy is kept at an optimum. BIS is a method for measuring bioimpedances
using a frequency spectrum between 5 kHz and 1 MHz with a current between 500 μA and 10 mA.

Usually, whole-body BIS measurements are accomplished using one electrode pair to inject the current and one electrode pair to measure the voltage at wrist and ankle so that four electrodes have to be used for one measurement. The resulting impedance curve represents a complex cole-cole curve (cf. fig. 2, left).

Fig. 2. Whole-body BIS measurement, typical impedance progression and equivalent circuit diagram

The model which fits very well to reality is represented by the equivalent circuit for this plot shown on the right side of fig. 2, whose impedance can be described by the following formula. Here \( C_m \) is the membrane capacity, \( R_e \) the extracellular, \( R_i \) the intracellular resistance and \( R_\infty = R_e || R_i \) [6].

\[
Z(\omega) = R_\infty + \frac{(R_e - R_\infty)}{1 + (j\omega C_m (R_i + R_e))^\alpha} \tag{1}
\]

Using these resistances, extra- and intracellular volume, total water, fat free mass, fat mass and muscle mass can be calculated [7]. The capacitor representing the cell membrane is a constant phase element (CPE) because the semi circle calculated [7]. The capacitor representing the cell membrane total water, fat free mass, fat mass and muscle mass can be compared to reference methods for detecting the body composition, [9]. Segmental and whole-body measurements have been compared to reference methods for detecting the body composition, such as Dual Energy X-Ray Absorpiometry (DEXA), \(^{40}\)K or \(D_2O\) solution method.

DEXA technology uses two different x-ray sources for emitting x-rays through the human body. A detector receives the non-absorbed radiation which depends on the density of the irradiated tissue. Thus, bone density and body fat can be calculated. Comparing segmental and whole-body measurements with fat free mass (FFM) assessments by DEXA, both bioimpedance methods generate correct values. In addition, BIS measurement results of single segments show high correlations with results of DEXA analysis of the same segments [10], [11].

The second reference method introduced here is the \(^{40}\)K method. \(^{40}\)K is a radioactive potassium isotope which is administered orally. It preferably accumulates in body fat and there emits x-rays when decaying. ECW and ICW measured by segmental BIS and the \(^{40}\)K method show good correlations [12].

The other substance taken as reference method is deuterium oxide (\(D_2O\)), also called heavy water, which is taken orally and is distributed in all body tissues except fat. By taking a blood sample and measuring the \(D_2O\) content in plasma, the total body water can be calculated. Segmental measurements are superior to whole-body measurements when detecting the hydration status compared to \(D_2O\) measurements [13]. It has been also shown without reference measurements, that thoracic segmental BIS measurements are better than whole-body measurements concerning the hyperhydration detection for dialysis patients [14]. To sum it up, the reason why segmental measurements and simulations have been accomplished is that several studies showed that segmental BIS produces reliable and in some cases even better results than conventional whole-body BIS.

III. METHODS

Classically, the body is divided into five segments: arms, legs and thorax. However, within this work the body was divided into nine segments: thighs, knees, lower legs, arms and thorax (cf. fig. 3). In addition, these segments have been approximated by frustums to match the non-cylindrical geometry of each segment individually by using the volume for calculating the body compositions of the segments. Each segment of the lower extremities consists of the tissues fat, bone and muscle.

Fig. 3. Classical and used segmental subdivision
All segments have been simulated using FIT and an anatomical data set of a male human. The program used for this is CST EM Studio® from Computer Simulation Technology, Darmstadt, Germany. The data set is based on the Visible Human Data Set from the National Library of Medicine, Maryland, USA and provides resolutions from 1x1x1 mm to 8x8x8 mm [15]. The origin of this data is Joseph Paul Jernigan, an executed prisoner, who has been frozen into gelatin after death. His frozen body was then cut into more than 1800 slices, so-called cryosections. These slices have been digitized by using MRI and CT with an image resolution of 4096x2700 pixels and a 24 bit color depth. At the moment, there are over 2000 licences sold in 48 countries regulating the usage of this data set. This work uses an anatomical data set created by MVR Studio GmbH, Loerrach, Germany.

This data set already contains segmented voxels for several tissues. Since voxels contain no volume data for a certain tissue, the voxel data had to be converted into volume data. First, all tissues were converted into stereolithography (STL) files. STL data contains surface geometries composed of triangles, represented by polygon meshes, enclosing the different tissues. This enclosed area can be converted into volume data. That way, every tissue has been converted into a volume. By using boolean operations, all tissues have been combined to form the whole body. Therefore, one volume containing all tissues has been created and used as a fat meta structure into which all other tissues have been inserted by subtracting them from the meta tissue. Since the original voxel data contains no information about skin, it is not included in the volume data. To be able to include skin in the simulations, 5 mm skin thickness has been added at the electrode sites. After that, electrodes composed of an aluminium and a PEC (perfect electric conducting) layer have been added. The resulting volume model consumes 3.3 GB RAM.

The PECs have been connected to a fixed voltage. To assess the complex current, the current density over transversal angles, represented by polygon meshes, enclosing the different tissues. This enclosed area can be converted into volume data. That way, every tissue has been converted into a volume. By using boolean operations, all tissues have been combined to form the whole body. Therefore, one volume containing all tissues has been created and used as a fat meta structure into which all other tissues have been inserted by subtracting them from the meta tissue. Since the original voxel data contains no information about skin, it is not included in the volume data. To be able to include skin in the simulations, 5 mm skin thickness has been added at the electrode sites. After that, electrodes composed of an aluminium and a PEC (perfect electric conducting) layer have been added. The resulting volume model consumes 3.3 GB RAM.

The simulation results were analyzed using frequency response locus plots which resemble cole-cole curves (cf. fig. 2, left), although the curve progression deviates slightly. Furthermore, the calculated values of the simulation results yield higher impedances in relation to measured values found in literature and thus they have been corrected by a factor which has been calculated to divide the impedances (cf. tab. I).

\[
\mathbf{L} = \int_{\mathbf{A}} \left( \mathbf{\mathbf{J}} + \mathbf{\frac{\partial \mathbf{\mathbf{D}}}{\partial t}} \right) \cdot d\mathbf{A} = \int_{\mathbf{A}} \left( \mathbf{\mathbf{J}} + j\omega \mathbf{\mathbf{D}} \right) \cdot d\mathbf{A} \quad (6)
\]

The material of the borders of the cubic simulation domain have been set to PEC. In addition, the interspace between simulation object and boundaries has been filled with vacuum (permittivity \( \epsilon_r = 1 \), conductivity \( \sigma = 0 \)). After having set the mesh density to create 2 million tetrahedrons, the simulation consumed 5 GB RAM and took 25 hours per sweep for the lower extremities. A whole body simulation would have taken 72 hours per frequency. Apart from knee, thigh and lower leg, knee-to-knee and foot-to-foot measurements have been simulated additionally as further scenarios. The impedances obtained by the simulations have been analyzed in Matlab® to compute extra- and intracellular resistances. The calculation frequency ranged from 5 kHz to 5 MHz, covering the measuring range of common BIS-analyzers.

For validation purposes, each segment has been measured at five male subjects with similar age (26-28 years) and Body Mass Index (21-25.5). The measurement device was a Xitron Hydra 4200 from Xitron Technologies, San Diego, USA. Standard adhesive electrodes from Fresenius Medical Care, Bad Homburg, Germany with a size of 19 mm x 80 mm have been used. All subjects were not allowed to drink and eat two hours before the measurements began. The subjects changed from an upright to a supine position remaining supine for 30 minutes so that a fluid shift from the lower extremities to the rest of the body occurred. To gather information about this shift, whole-body bioimpedance has been obtained after each segmental BIS measurement [16].

**IV. RESULTS**

Before the human model has been built and used for simulation, the ability of the simulation program to simulate BIS has been tested by creating a capacitor with a muscle dielectric. This capacitor was intended to reproduce the measurements accomplished by Gabriel et al. who measured permittivity and conductivity of human tissues between 10 Hz and 1 GHz using network analysers. The results showed that the CST software could correctly reproduce the measurements by Gabriel et al. with \( \alpha \), \( \beta \) and \( \gamma \) dispersion regions.

The model used for the simulation results is shown in fig. 4. The D-Field results of a foot-to-foot measurement simulation are presented here by arrows floating through the body from the left foot to the right foot. Thickness and direction of the arrows symbolize the displacement current density and its direction.

The simulation results were analyzed using frequency response locus plots which resemble cole-cole curves (cf. fig. 2, left), although the curve progression deviates slightly. Furthermore, the calculated values of the simulation results yield higher impedances in relation to measured values found in literature and thus they have been corrected by a factor which has been calculated to divide the impedances (cf. tab. I).
Electrodes

Table I

<table>
<thead>
<tr>
<th>Segment</th>
<th>(R_{e, \text{sim}}) [(\Omega)]</th>
<th>(R_{e, \text{literature}}) [(\Omega)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot-to-foot</td>
<td>1915.9</td>
<td>243.8</td>
</tr>
<tr>
<td>Leg</td>
<td>1115.8</td>
<td>243.8</td>
</tr>
<tr>
<td>Knee-to-knee</td>
<td>252.9</td>
<td>54.3</td>
</tr>
<tr>
<td>Lower leg</td>
<td>973.4</td>
<td>138</td>
</tr>
<tr>
<td>Thigh</td>
<td>238.4</td>
<td>27.1</td>
</tr>
<tr>
<td>Knee</td>
<td>238.9</td>
<td>78.7</td>
</tr>
</tbody>
</table>

To verify the simulations, segmental BIS measurements on five subjects (\(n = 5\)) have been carried out. The sequential whole-body BIS reference measurements, gathered to measure the fluid shift due to a position change, have been used for the correction of the intra- and extracellular resistances as shown in [16]. An impedance shift towards higher impedances over 30 minutes was observed (cf. fig. 5).

Fig. 6 shows the corrected simulation results and its curve fit (dashed line) for a foot-to-foot simulation.

Comparing this plot to the frequency locus plot of the measurement results (fig. 7), one can see that both complex impedances lie within the same range.

Using the correction factors and a curve fit for the results of the simulations, measurements and simulations produced similar results (cf. tab. II).

Table II

<table>
<thead>
<tr>
<th>Segment</th>
<th>(R_{e, \text{sim}}) [(\Omega)]</th>
<th>(R_{e, \text{m}}) [(\Omega)]</th>
<th>(R_{i, \text{sim}}) [(\Omega)]</th>
<th>(R_{i, \text{m}}) [(\Omega)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot-to-foot</td>
<td>479.85</td>
<td>418.79</td>
<td>642</td>
<td>855.28</td>
</tr>
<tr>
<td>Leg</td>
<td>276</td>
<td>239.8</td>
<td>333</td>
<td>411.07</td>
</tr>
<tr>
<td>Knee-to-knee</td>
<td>86.46</td>
<td>92.4</td>
<td>79.53</td>
<td>131.1</td>
</tr>
<tr>
<td>Lower leg</td>
<td>176.97</td>
<td>135.01</td>
<td>222.38</td>
<td>212.1</td>
</tr>
<tr>
<td>Thigh</td>
<td>55.59</td>
<td>50.96</td>
<td>67.14</td>
<td>70.2</td>
</tr>
<tr>
<td>Knee</td>
<td>57.49</td>
<td>53.9</td>
<td>73.3</td>
<td>96.07</td>
</tr>
</tbody>
</table>

V. DISCUSSION

The task of this work was to derive correlations of segmental BIS and whole-body BIS measurements and to compare them...
with simulations of segmental BIS measurements. Promising results have been obtained comparing measurements and simulations.

First, it has been shown by segmental BIS measurements that intra- and extracellular resistances of segments correlate with whole-body resistances. The fluid shift from the lower extremities to the rest of the body during these measurements is explainable due to the position change of the subjects [17]. Second, results of the measurements reveal on the one hand that extremities have the highest relative share on the whole-body resistances which is explainable because they contain joints which are composed of low conducting bone tissue. On the other hand, the thighs contains much more good conducting material and thus they have the lowest influence on the whole-body resistance. Third, comparing measurements and simulations, this work also showed that simulations offer a reliable method for imitating processes in the body during BIS because they deliver the same dependencies of segments and the whole body.

However, some future work has to be done. Reasons for the simulation model to produce too high absolute impedances should be analyzed further to consider it in future simulations. The main reason could be the coarse model resolution of 8x8x8 mm that leads to inaccuracies. During the conversion process small structures can be lost. Combined with some volumes such as small blood vessels (e.g. arterioles), which are too small to be considered in the model, these volumes are replaced by the meta volume fat tissue which is less conducting. Another known problem exists in this case because in the human body small blood vessels collapse after death due to pressure losses. This means that these volumes are not available, even in the finest voxel data. Another reason for higher impedances is the lack of skin in the original model. The added 5 mm skin volume does not reflect realistic impedances. Last but not least, a 2-point-measurement has been carried out in this work, which means that in fact, 8 cm tissue impedance should be subtracted for a 4-point-measurement from the simulated results.

Concerning the measurements, it is necessary to gather results from more subjects of all genders and ages to be able to generalize the findings of this work.

Considering that the intra- and extracellular resistances of segments are correlated to the whole-body resistance, it has been shown that it is possible to apply the body composition drawn from segments to the composition of the whole body. This leads to the possibility of using knee-to-knee measurements to monitor the body composition of geriatric patients. These measurements can be obtained e.g. from shorts worn by the patients containing integrated electrodes. The measured data could be exchanged via wireless networks to the attending doctor for a 24/7 supervision of the patient.

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