Portable Bioimpedance Spectroscopy device and textile electrodes for mobile monitoring applications

L. Beckmann1, M. Jacob1, C. Hoog Antink1, A. Cordes1, R. Pikkemaat1, N Jungbecker2, T. Gries2 and S. Leonhardt1
1Philips Chair of Medical Information Technology, RWTH Aachen University, Pauwelsstr. 20, 52074 Aachen, Germany
2Institut für Textiltechnik, RWTH Aachen University, Otto-Blumenthal-Str. 1, 52074 Aachen Germany

E-mail: beckmann@hia.rwth-aachen.de

Abstract. A balanced body composition is necessary for a person’s health and performance. Therefore, it is important to control the body composition continuously since complications and diseases due to dehydration often appear gradually. Based on these facts a miniaturized mobile Bioimpedance Spectroscopy device was developed that can be integrated into clothing and allows the continuous monitoring of a person’s body water. The implemented system has been tested using different body models. The first measurements showed very precise and stable results. Besides the portable measurement system, textile electrodes are needed for continuous long term monitoring. Therefore, special textile electrodes were developed, tested and evaluated. The electrodes are structured in a specific way leading to a rougher surface. Such a surface improves the interface impedance and therefore optimizes the connection between electronic hardware and body. For comparison, five different structured electrodes were manufactured and tested on a special test setup that allows reproducible interface-impedance measurements using a dummy made of agar-agar to simulate the skin. It could be shown that the surface structure significantly influences the interface impedance in a positive way as compared to standard plane textile electrodes. In the future, a combination of the miniaturized BIS electronic and the structured textile electrodes could allow reproducible long term monitoring of a person’s body composition.

1. Introduction
Textile integrated measurement systems are very important applications in the future. Such systems allow long-term monitoring in order to improve the recovery of patients as well as to simplify early diagnosis. One scenario for long-term measurements is monitoring the body composition of elderly people. Such people gradually lose the physiological attraction of drinking and eating, as a consequence of the natural ageing process, which can lead to age anorexia and dehydration with severe consequences. Bioimpedance Spectroscopy (BIS) measurements may allow the continuous monitoring of body composition. By now, the accuracy of BIS measurements has been demonstrated in several clinical trials [1]. Even if BIS is a helpful application as early warning system, most measurement devices are still quite big and are not portable or integrated into clothes, which is necessary for mobile monitoring scenarios. In the past a few miniaturised hardware systems were developed and presented e.g. by Vuorela [2] and Beckmann [3]. But they are still quite big or restricted in terms of measurement resolution and frequency range. Besides the hardware for a
complete integration, textile electrodes are important. Several researchers are currently developing and testing such electrodes for different applications. First test for BIS measurements were presented by Vuorela [2] and Medrano [4]. The major problem of using textile electrodes is the high interface impedance between electrode and skin due to the lack of hydrogel. Therefore, in this article textile electrodes are presented that improves the electrode-skin-contact due to special structured surfaces.

2. Hardware Realization

2.1. Hardware Design
A portable BIS measurement device was developed, that allows continuous body composition monitoring. The system consists of two small boards as shown in Fig. 1. Embedded into a small box the system can be worn on the body. The device is battery-driven and measures the impedance between 5 kHz and 1 MHz. The measurement current is generated using a signal generator and an additional current source. During a measurement the injected current and occurring voltage is measured and separated into real and imaginary part using a quadrature demodulator. The measurement data are converted and saved on a microcontroller. Finally, the data for each frequency are sent to a PC or PDA for further analysis. Additionally, the measurement device features a special safety circuit to guarantee adherence to the IEC 60601-1 electrical safety standards.

Figure 1. Block diagram and picture of the new developed hardware.

2.2. Results
The new developed measurement device was tested and evaluated using different test circuits. The test circuits consist of a Cole-Cole circuit built up with passive components simulating the whole body of a person or different body segments (e.g. thigh). Additionally, the circuits are equipped with further passive components to simulate the electrode-skin-contact. After sending the measured impedance values to the PC the Cole-Cole parameter were calculated and compared to the original data of the test circuit components. Table 1 shows the original values, the measured values as well as the calculated relative error.

For the whole body measurement the relative error for all Cole-Cole parameters is around 3.4%, especially $R_e$ was measured very precise with a deviation of only 0.66%. For thigh measurements the error increases slightly to a maximum of 5.56%. Compared to whole body measurements the measurement signals during a thigh measurement are much smaller ($R_e = 681 \Omega$ compared to $R_e = 54 \Omega$). Smaller signals are more difficult to detect and are stronger influenced by the existing noise. However, by adjusting the measurement amplifier to the specific thigh measurement range, even better results could be achieved in the future.
Table 1: Original and measured Cole-Cole parameters in two dummy measurements

| Body Segment | Parameter | Original Data | Measured Data | Relative Error |
|--------------|-----------|---------------|---------------|----------------|
| Whole Body   | $R_e$     | 681 $\Omega$  | 685.6 $\Omega$| 0.66 %         |
|              | $R_i$     | 909 $\Omega$  | 877.9 $\Omega$| 3.41 %         |
|              | $C_m$     | 3.3 nF        | 3.35 nF       | 1.52 %         |
| Thigh        | $R_e$     | 54 $\Omega$   | 51.2 $\Omega$ | 5.56 %         |
|              | $R_i$     | 56 $\Omega$   | 57.7 $\Omega$ | 2.68 %         |
|              | $C_m$     | 47 nF         | 49.2 nF       | 4.68 %         |

3. Textile Electrodes

3.1. Materials
Besides the small measurement hardware, textile electrodes are important ingredients for integrated portable measurement scenarios. Therefore, 5 different textile electrodes were developed and tested. Four of the newly developed textile electrodes are structured which leads to a rougher surface and improve the interface-impedance and optimizes the connection between hardware and body. All textile electrodes are made of silvered polyamide fibres mixed with other polyamides and spandex. The spandex fibres make the final textile very elastic and therefore very comfortable to wear. Fig. 2 shows the structured surfaces of the new developed textiles.

![Figure 2. Surface of the new developed textile electrodes.](image)

3.2. Results
For testing the suitability of the new electrodes, tests with five elderly volunteers were made. Figure 3B shows the interface impedance measured with the five different textile electrodes as well as with standard glued electrodes as a reference exemplarily for one volunteer. The standard glued electrodes are electrodes that are used for measurements with the Bioimpedance Analyser Xitron Hydra 4200, from Xitron Technologies, USA.

The measurements made with volunteers have one severe disadvantage. They are quite difficult to analyse in order to investigate the suitability of the electrodes for BIS measurements. Even if the interface impedance is different for every electrode, the measurements are very difficult to reproduce and to compare between the volunteers since the dielectric properties of human skin change from person to person and within hours. To avoid such measurement influences the electrodes were also tested using a special electrode test setup. The test setup contains a skin dummy made of agar-agar and allows measuring the interface impedance within a frequency range of 5 kHz – 1 MHz and for different contact pressures.
More details about the setup can be found in [5]. Fig 3A shows the interface impedance measured with the test setup at a stable contact pressure of 9.73N. Obviously, the interface impedance decreases for higher frequencies but differs strongly between the 5 textile electrodes. Textile electrode 5 has the highest interface impedance around 300 $\Omega$, textile electrode 1 the lowest impedance around 160 $\Omega$. Three of the four structured textile electrodes have smaller interface impedances than the non-structured reference electrode 3. This result shows that a structured surface improves the electrode-skin-contact and lead to smaller interface impedances, whereas the structure of textile electrode 1 seems to be best suitable for measurements.

4. Discussion
The textile integration of BIS measurement systems is becoming more and more important for various applications. Therefore, a miniaturized hardware as well as textile electrodes were presented in this paper. The measurement error of the hardware was beyond 3.1% and 5.6% respectively, which is quite good for such small hardware designs. Additionally, structured electrodes were developed and tested. It could be shown that the structured surface influences the electrode-skin-contact and improves the interface impedance. In the future, the newly developed hardware and the structured electrodes should be combined for specific measurement application to allow very precise long-term Bioimpedance monitoring.

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