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Metrological characterization of a combined bio-impedance plethysmograph and spectrometer

Erika Pittella[a,*], Emanuele Piuzzi[a], Emanuele Rizzuto[b], Stefano Pisa[a], Zaccaria Del Prete[b]

[a] Department of Information Engineering, Electronics and Telecommunications, Sapienza University of Rome, 00184 Rome, Italy
[b] Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, 00184 Rome, Italy

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A B S T R A C T

In this paper, the design and characterization of a device, able to analyze the electrical bio-impedance in the frequency domain and its variations with time, is presented. The whole system design, that employs a tetra-polar electrode configuration, a specifically developed printed circuit board, and a data acquisition card connected to a PC, is presented. The measurement system is controlled through LabVIEW virtual instruments. Different reference resistors and RC networks, with impedance values lying in the physiological range of bio-impedances, have been used for assessing the systematic and random uncertainty contributions, and to derive the calibration curves necessary to correct the systematic effects of the developed instrument. The obtained results show that it is possible to achieve excellent metrological performances with the proposed system, that is suitable to be developed in a low-cost and portable version. Two possible applications of the instrument are shown, i.e. cardio-respiratory activity monitoring and bioelectrical impedance spectroscopy.

1. Introduction

Analysis of the complex electrical impedance of biological tissues allows to obtain a large amount of information about the tissue anatomy, physiology, and pathology [1–4]. Electrical bio-impedance depends on four major factors: (i) the tissue and subject under study, (ii) the physiological and physiochemical variations that occur within the tissues, (iii) the variation occurring between healthy and unhealthy tissues, and (iv) the frequency of the applied signal.

Electrical bioimpedance measurements have been mainly used in two applications [5]. The first consists in the study of small changes of the transthoracic impedance related to respiration (breathing) or heart beating, measured by injecting, inside the thorax, a current with constant amplitude and frequency. This technique, known as impedance plethysmography (IPG) gives continuous quantitative and qualitative information on volume changes in the lungs [6–12], in the heart [13,14], in the veins and peripheral arteries [15–26].

The second and most recent application concerns the determination of body composition, such as the body fluid volume, the body fat percentage and other parameters. This technique, called bioelectrical impedance analysis (BIA), exploits the measured body impedance [27]. Further information on body composition can be achieved by measuring the impedance as a function of the frequency (bioelectrical impedance spectroscopy - BIS) [28].

Currently, IPG is widely used in multi-parameter monitors in order to provide information on breath activity [8–10,14], and it is employed in specifically developed instruments suitable to monitor heart activity [14], or to perform diagnosis on the peripheral vascular system [16–20]. BIA and BIS, instead, are implemented through dedicated instruments, for studying the composition and electrical impedance frequency response of the body [28–33]. Generally, BIS devices use the frequency sweep technique [30]. However, a broadband solution has been also proposed based on an optimal multisine excitation [34].

At present, to the authors' knowledge no low-cost, portable and flexible solution is available, suitable to perform, at the operator's discretion, all of the above-mentioned diagnostic analysis. Indeed, very sophisticated devices exist for the estimation of the body composition in healthy individuals, like the ImpediMed SFB7 that scans 256 frequencies between 4 kHz and 1000 kHz [35]. Integrated solutions, like the AFE4300 [36] analog front-end for weight scaling and body-composition measurements, designed to be used on the human body, are also available. However, the afore-mentioned systems do not allow to perform plethysmographic examinations. On the other hand, different integrated on-chip impedance analyzers are available on the market, like the high precision impedance converter system AD5933 [37]. Such solutions would provide an accurate, flexible and straightforward solution for developing a general-purpose bio-impedance analyzer: unfortunately, such devices are not specifically designed for direct use on

* Corresponding author.
E-mail address: erika.pittella@uniroma1.it (E. Pittella).

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the human body, and lack the related certifications, making their use as bio-impedance meters not allowed.

In this paper, a simple measurement device able to carry out both time and frequency-domain bio-impedance analyses is presented and metrologically characterized. The system, which employs a tetra-polar electrode configuration, consists of an analog printed circuit board and a data acquisition (DAQ) card connected to a PC. The DAQ card and analog board can be powered by a rechargeable battery, which makes the system isolated from the mains supply and inherently safe with reference to AC and ground leakage currents. The measurement system is controlled through LabVIEW virtual instruments (VI's), which implement the stimulation waveforms, as well as data processing. Even though the system, in its current implementation, is neither portable nor low-cost, because of the use of a high-accuracy 16-bit DAQ card and of LabVIEW-based signal processing, the main aim of this study is to demonstrate that a flexible and self-developed bio-impedance analyzer can provide excellent metrological performances. On the other hand, the proposed solution can be turned into an actual portable and low cost system, simply replacing the DAQ card and PC-based data processing by a 16-bit ADC [38] and a digital signal processor (DSP) [39], making the cost of the entire system lower than 100 $. Such solution would be of great interest in view of potential e-health application scenarios and of home-care of chronic patients and elderly people.

The remainder of the paper is organized as follows. The proposed system configuration is described in Section 2, while in Sections 3 and 4 the hardware design and the software implementation are detailed, respectively. In Section 5, the device metrological characterization is presented. Section 6 shows experimental results obtained with the device for different biomedical monitoring and diagnosis applications. Finally, in Section 7 conclusions are drawn.

2. System configuration

2.1. Measurement system

Fig. 1(a) shows the measurement system configuration, constituted by a laptop that controls the measurement procedure through a LabVIEW virtual instrument (VI), a device for generating and acquiring signals (DAQ card), a terminal block, a battery, an analog board for signal conditioning, and four electrodes.

The DAQ card, linked to the PC through a USB cable, synthesizes a sinusoidal voltage signal with a given amplitude and frequency. This signal is delivered to the analog board, which includes a voltage-to-current converter; the resulting current signal is injected in the body segment by two adhesive electrodes. Simultaneously, the DAQ card acquires the potential difference detected by other two adhesive electrodes placed on the same body segment, alongside with the voltage across a shunt resistor, used to measure the injected current. These acquisitions are synchronized by a LabVIEW VI that controls the measurement procedure.

The impedance magnitude is obtained as the ratio between the sinusoidal voltage waveform amplitude measured across the body segment and the sinusoidal current waveform amplitude at a given frequency; the difference between voltage and current waveform phases provides the impedance phase angle.

As concerns the electrodes, a quadrupole configuration is adopted, in which two stimulation electrodes (red[1] squares in Fig. 1) inject the current, while two detection electrodes (blue squares in Fig. 1) acquire the associated voltage drop. This configuration provides an impedance measurement that has a low skin-electrode interface dependence [1,40].

Finally, the electrodes can be placed in different body segments, according to the intended application [Fig. 1(b)]. As an example, Fig. 1(b)-I shows a typical electrode arrangement for cardio-respiratory activity monitoring, while Fig. 1(b)-II the electrodes configuration for the peripheral vascular system monitoring.

The analog board receives the required voltage supply from the DAQ card, which can be powered by a 12-V rechargeable battery, making the whole device isolated from the mains supply.

2.2. Signal generation and acquisition

The stimulation signal required to perform the impedance measurement is synthesized by the DAQ card as a voltage signal, with a time behavior imposed by the LabVIEW VI, and is then transformed into a current signal in the analog board, thanks to the voltage-to-current converter.

Indeed, even though more elaborate schemes are available [41], the choice has been made to keep the hardware as simple as possible.

During the instrument design stage, the goal was to develop a flexible solution, suitable to carry out both measurement of the impedance behavior as a function of the frequency, and of the impedance time behavior of a body segment at a given frequency. To this end, two different VIs have been developed. For the frequency analysis, the magnitude and phase are measured for a user-defined set of frequency points chosen in the 1–100 kHz frequency range.

The lower frequency limit was selected considering that at frequencies between 50 Hz and 1 kHz neurons are very sensitive to the current and international safety standards limit the allowed current to 0.1 mA [42]. This value gives rise to low voltage with respect to the instrumentation amplifier sensitivity. Between 1 kHz and 100 kHz, current limits grow (see Table 1) thus relaxing the sensitivity constraints. As for the upper limit, it is dictated by the employed DAQ card (NI USB-6251), which is able to acquire input signals with a maximum sampling rate of 1 MS/s (aggregate value considering all channels used).

In order to limit interference, wires connecting the board to electrodes are twisted together. However, if impedance measurements at higher frequencies are required, a DAQ card with a higher sampling frequency can be used. In this case, suitable electronic components might be added to the analog board for driving an active shield in order to reduce interference on the measured signals [43].

The device measures the impedance at each selected frequency, in a sequential manner, by generating for each point a sinusoidal waveform with zero mean (to avoid injecting a DC component) [30]. The signal is composed of 10 cycles with an amplitude depending on the signal frequency. Indeed, it is necessary that the amplitude values of the injected current meet safety requirements, such as those prescribed by IEC 60,601 [42], which are frequency dependent (see Table 1).

For patient safety, constant injected current level control is carried out by a specific software module within the LabVIEW instrument. If the current value overcomes the predefined limit, the software module raises an alarm and halts the current injection.

The measurement duration is of the order of a few seconds (depending on the number of frequency points), and the program allows to perform several consecutive measurements, in order to evaluate measurement repeatability.

In the time behavior modality, a similar program is employed. However, the frequency sweep is no longer present and measurements are repeated over time at a fixed frequency with a user-defined sampling step.

3. Hardware design

3.1. Circuit diagram

Fig. 2 shows the circuit scheme comprising the various circuit elements and the NI USB-6251 DAQ card [44]. The connection between

[1] For interpretation of color in Figs. 1, 3 and 6, the reader is referred to the web version of this article.