Development and testing of a customizable and portable bioimpedance spectroscopy meter (BioZspectra-v1)

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Abstract. A portable, 4-electrode bioimpedance spectroscopy meter called BioZspectra-v1 was developed, based on thinking about a cost-competitive, highly flexible, nimble and easily customizable solution for the differing needs of researchers and scientists. There are diverse alternatives on the market but they are costly and designed for specific applications. However, research into new topics requires the manipulation of raw data and different configurations that BioZspectra-v1’s hardware and software can supply, enabling customized experiments. Output current is available in 4 discrete values: 10 µA, 20 µA, 40 µA and 100 µA; frequency range is from 1 Hz to 100 kHz, with 0.1 Hz resolution; the communication port is either USB or Bluetooth, the spectrum recording can be pseudo-real-time, and point-by-point and wide types of cell connector can be used. In addition, the circuit topology is as simple as possible, without detriment to performance; weight is light, for field and in situ applications and the design complies with IEC-60601-1, for patient safety. The equipment was tested obtaining a maximum measurable impedance of 100 kΩ with an error of below 2%, and a minimum of 10 Ω with an error of below 1.5%. Applied current error was below 1.5% for the whole frequency range.

1. Bioimpedance Spectroscopy and meters

Bioimpedance Spectroscopy is the electrical impedance measurement of biological tissues that evaluates their electrical properties on a well-defined frequency range. There are many applications of this technique, i.e. impedance cardiography, tissue characterization in urology, body composition analysis, and disease detection, among others [1].

An abundant selection of impedance meters for specific applications exists in the biological instrument market, designed to provide healthcare staff with biological parameters of body or tissue. However, they fail, not only to provide flexibility to carry out other tests for research purposes, but also to allow modification of certain parameters (IMPEDIMED and BODYSTAT are two companies that produce bioimpedance meters such as the SFB7 and MultiScan5000 ). On the other hand, several papers have reported design and development of a great variety of bioimpedance meters for a great diversity of applications to achieve better solutions for specific problems [2–4]. Meanwhile, some researchers have focused on optimizing the hardware to improve performance of voltage-controlled current sources [5,6], while others focus on developing portable, user-friendly and wearable equipment [7–9].

In this paper, we present the development of a PC-controlled bioimpedance meter, called BioZspectra-v1, designed based on thinking about relatively flexible hardware and software that, with a few changes, can adapt to different applications, keeping the equipment portable and easy to use.
This version allows the measurement of the real part of impedance only, based on the fact that, in a linear system, the imaginary part is related to real part by Kramers-Kronig relations and can be calculated by computational algorithms [10].

2. BioZspectra-v1
This bioimpedance meter is comprised of six main modules: a current generator, a voltage measurement, a current measurement, control and processing, communication and a power supply. A block diagram of it is shown in Figure 1.

2.1. Current generator
This comprises two blocks; a signal generator and a modified Howland current source. The signal generator is an AD9833, configurable for two ranges of frequencies by hardware. For high frequency (dispersion zone β), the clock source is a crystal oscillator of 24 MHz. For low frequency (dispersion zone α), the clock source is a PWM from a control and processing module at 1 MHz. A low-pass filter is implemented at an output of AD9833 with a cutoff frequency of 1 MHz in order to diminish impurity from digital synthesis of the signal.

The Howland current source was implemented with a 145 MHz bandwidth op-amp AD8065. Printed circuit board (PCB) layout techniques were taken into account and circuits for active drive of coaxial shield were implemented in order to reduce parasitic capacitances that decrease the output impedance of the current source. Generalized impedance converter (GIC) circuits were not
implemented because they have a narrow band. For equipment with multiple selectable frequency and high bandwidth, numerous GIC circuits will be necessary, i.e. the KHU MARKII in a range of 10-500kHz has 4 GIC circuits [2]. This will also increase the area of PCB layout. In addition, there is a report that current sources with GIC circuits show similar behavior than a modified Howland source with high frequency, low capacitance op-amps [11].

The amplitude range of the current signal is hardware-configurable. For example, for in-vivo applications, output currents are 10µA, 20 µA, 40 µA and 100 µA. For other applications, the equipment can be modified to obtain 100 µA, 200 µA, 400 µA and 1 mA (for characterization of materials or ex-vivo measurements). The maximum possible current is 10 mA and the minimum is 1 µA.

2.2. Voltage measurement
The electrometer was carried out with an op-amp OPA656 which has an input impedance of 1 TΩ in parallel with 0.7 pF in differential-mode and 1 TΩ in parallel-mode with 2.8 pF in common-mode. This circuit has the active drive of a coaxial shield in order to diminish the capacitance effect of cables. The voltmeter is followed by a band pass filter with 1 MHz bandwidth. Lower cutoff frequency is configurable by hardware to enable two modes with two values: 10 Hz and 0.1 Hz. The first mode is the operation in pseudo-real time in the beta region (fc=10 Hz). The second mode is the operation in alpha and beta region for point-by-point acquisition (fc=0.1 Hz). A variable-gain amplifier stage controlled by software, either manually or automatically, allows amplification of low-level voltage signals. The gains are 1, 10, 100 and 1000 V/V.

2.3. Current measurement
A current-to-voltage converter in trans-impedance configuration was implemented. This configuration allows current measurement without compromising equipment compliance voltage. This stage was carried out with OPA656. Current-to-voltage converter output voltage then goes through a filtering and conditioning stage identical to that of the voltage measurement module.

2.4. Control and processing
This module comprised a Digital Signal Controller (DSC) which: controls the signal generator and amplifier stages, acquires voltage and current signals, receives orders from the PC and delivers measurement data. The acquisition is carried out by the internal, analog-to-digital converter (ADC) of the DSC. The maximum sampling rate is 100 kSPS with 12-bit resolution. Data and request commands are sent from a serial communication interface (SCI) at 115,200 bps.

2.5. Communication
To establish a link between BioZspectra-v1 and the PC, there are two hardware-configurable options:

To set up the equipment for in-vivo applications, a Bluetooth module is adapted to work as a serial COM port. In this case, the wireless transfer of data avoids physical connection with the PC to ensure patient safety according to IEC-60601-1.

For other applications that do not require compliance with IEC-60601-1, a USB link can be installed. This configuration shows less power consumption, a higher data transfer rate, less radiation emission and a permanent link. This could be the best choice for difficult field or industrial settings.

2.6. Power supply
BioZspectra-v1 has internal circuits to regulate appropriate voltage levels, guaranteeing the best performance of each module. Input should be 5 V/1 A that could be supplied by three options: a commercial power bank: the use of batteries allows compliance with IEC-60601-1 because the equipment is physically isolated from high voltage of the electrical grid. The second option is a medical-grade AC/DC adapter certified to comply with IEC-60601-1, and the third is an AC/DC adapter for ex-vivo and other applications.
2.7. Patient safety
The in vivo version of the BioZspectra-v1 has four capacitors in series with each electrode to avoid the pass of DC leakage currents. A plastic case is used for isolation of the electrical parts to avoid accidental contact with the patient. Diodes for ESD protection have been installed in the electrometer. The power supply can be a power bank with a special connector to avoid simultaneous charging and operation, or a medical-grade AC/DC adapter.

3. Results
We ran a series of tests in order to evaluate the performance of BioZspectra-v1, taking into account two aspects: 1. Ability to sustain a constant output current, 2. Ability to measure resistors without lacks in the spectrum at a whole range of frequencies.

3.1. Constant output current
We applied four currents to a 0.1% of the tolerance 10kΩ resistor and measured voltage drop with the help of Rigol DS1000E at a frequency range of between 1 Hz and 100 kHz, obtaining the current behavior shown in Figure 2. The maximum error was 1.5% for 100 μA. For the remainder of the currents, errors were below 1%.

![Figure 2. Output Current for 10 kΩ.](image)

3.2. Measurement of resistors, RC circuits and skin
We measured resistors of 0.1% tolerance from 10 Ω to 100 kΩ at 40 μA. In Figure 3, we can see the ability of BioZspectra-v1 to measure resistors up to 100 kΩ without lacking at high frequencies. The maximum error was 2% for 100 kΩ, and 1.5% for the remainder.

In Figure 4, we show the spectrum of two RC Randles circuits and one test on the skin. RC circuits were measured with four, 50 cm long cables at 10 μA.

The skin test was carried out on the left hand of the author, only with the purpose of seeing the performance of the equipment on a real biological tissue. For this, a flush tetra-polar probe of gold electrodes (1 mm in diameter), placed in a square configuration, 1 mm distance from each other, and a current of 10 μA, were used.
Figure 3. Measurement of some resistors.

Figure 4. Measurements of two RC circuits and skin. RC1: 150Ω in series with parallel of 1 kΩ and 22nF, RC2: 22 Ω in series with parallel of 9.1 kΩ and 10 nF.

4. Conclusions
A bioimpedance spectroscopy meter was developed which allows measurement of the real part of impedance from 10 Ω to 100 kΩ in a range of 1 Hz to 100 kHz, covering part of alpha and beta dispersion zones, with a maximum error of 2%. In this region, performance is better than that shown by the portable meter reported in [7] but BioZspectra v1 does not work properly above 100 kΩ. Other equipment has a smaller frequency range [8] and does not report the impedance measurement error [8,9].

The equipment current output has a planar behaviour in its operating frequency with a maximum error of 1.5%, with no need for GIC circuits, for the four current amplitudes. Other studies do not evaluate behaviour for different levels of current, which could change the equipment’s performance [7–9].
For patient safety regarding electrical hazards, the equipment was developed whilst taking into account the IEC-60601-1 directives.

The equipment was developed to allow multiple set-ups for diverse applications without the need to redesign the whole system. In future work, it will be very important to add the measure of the imaginary part, magnitude and phase in order to get better information about the electrical properties of tissue or other materials under test.

References
[1] González-Correa C A 2018 Clinical Applications of Electrical Impedance Spectroscopy *Bioimpedance in Biomedical Applications and Research* (Cham: Springer International Publishing) pp 187-218
[2] Oh T I, Wi H, Kim D Y, Yoo P J and Woo E J 2011 A fully parallel multi-frequency EIT system with flexible electrode configuration: KHU Mark2 *Physiol. Meas.* 32 835-49
[3] Chen X, Kao T-J, Ashe J M, Boverman G, Sabatini J E and Davenport D M 2014 Multi-channel electrical impedance tomography for regional tissue hydration monitoring *Physiol. Meas.* 35 1137-47
[4] Yang Y, Zhang F, Tao K, Wang L, Wen H and Teng Z 2015 Multi-frequency simultaneous measurement of bioimpedance spectroscopy based on a low crest factor multisine excitation *Physiol. Meas.* 36 489-501
[5] Bouchaala D, Shi Q, Chen X, Kanoun O and Derbel N 2012 Comparative study of voltage controlled current sources for biompeadance measurements *Int. Multi-Conf. on Systems, Sygnals & Devices* (IEEE) pp 1-6
[6] Zhang F, Teng Z, Zhong H, Yang Y, Li J and Sang J 2018 Wideband mirrored current source design based on differential difference amplifier for electrical bioimpedance spectroscopy *Biomed. Phys. Eng. Express* 4 025032
[7] Guimerà A, Gabriel G, Parramon D, Calderón E and Villa R 2009 Portable 4 Wire Bioimpedance Meter with Bluetooth Link (Springer, Berlin, Heidelberg) pp 868-71
[8] Patil A S and Ghongade R B 2016 Design of bioimpedance spectrometer 2016 *Int. Conf. on Advances in Computing, Communications and Informatics (ICACCI)* (IEEE) pp 2724-8
[9] Kukharenko I and Kotovskyi V 2017 Low power bioimpedance tracking system for stress and activity monitoring 2017 *IEEE 37th Int. Conf. on Electronics and Nanotechnology (ELNANO)* (IEEE) pp 288-91
[10] Miranda D A and Rivera S A L 2008 Determination of Cole–Cole parameters using only the real part of electrical impedance measurements *Physiol. Meas.* 29 669-83
[11] Wang W, Brien M, Gu D-W and Yang J 2007 A Comprehensive Study on Current Source Circuits 13th *Int. Conf. on Electrical Bioimpedance and the 8th Conf. on Electrical Impedance Tomography* (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 213-6