

Bioimpedance spectro-tomography system using binary multifrequency excitation

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Introduction

While both, the impedance spectroscopy and the impedance tomography, have already become well-established methods for exploring biological objects, their combination - bioimpedance spectro-tomography - offers a number of unresolved problems [1]. An important problem is ensuring the required measurement speed in the wide-band spectrometry of dynamic (time-varying) objects [2].

In this paper, we propose a way to adapt the fast impedance spectroscopy method [2, 3] (proprietary Quadra technology) for the tomography of time-varying bioimpedances. First, we present the instrumentation of the new spectro-tomography device. Then, we evaluate its function in experimental measurements with complex impedance phantom. We reconstruct spectro-tomographic images both in time-difference and frequency-difference mode. The method is also known as electrical impedance tomography.

Materials and Methods

Development of the Spectroscopy system

The Quadra main spectroscopy unit in fig.1 is built-up on the bases of digital signal processor (DSP) type TMS320F28069 from Texas Instruments, USA [4]. Besides the standard digital computing part, it contains a dual 16x16 bit multiply-and-accumulate (MAC) processing unit for performing the discrete Fourier transform (DFT). Especially important is the inclusion of a high-resolution (200 ps) pulse width modulator (PWM) for

generating the binary excitation voltage V_{EXC} at 80 MHz clock (fig. 2). As a result, real time spectral analysis becomes available after every 1 ms time interval at 15 frequencies: 1, 2, 3, 7, 11, 17, 23, 31, 43, 61, 89, 127, 179, 251, and 349 kHz, (fig. 3).

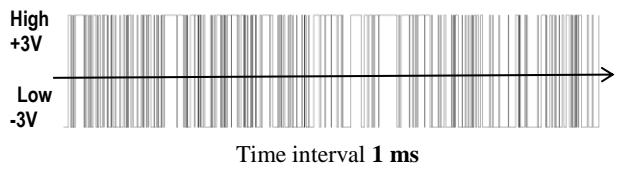


Figure 2: A full 1ms cycle of the binary excitation

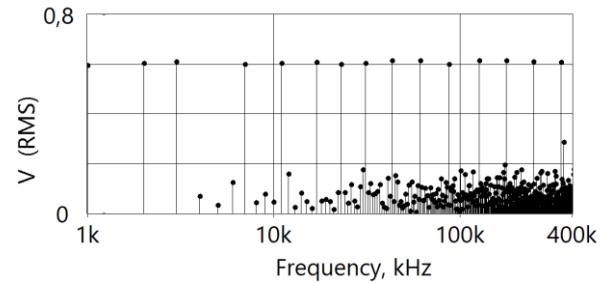


Figure 3: Spectrum of the binary excitation signal

To operate also as a tomography device, a versatile multiplexer (unit B in fig.1) was developed on the bases of a cross-point switch CD22M3494 from Intersil [4]. The cross-point switch allows switch over analog signals from any of its input pins to any of its output pins. All the 16 inputs/output pins are bi-directional for passing through both excitation and response signals. The order of

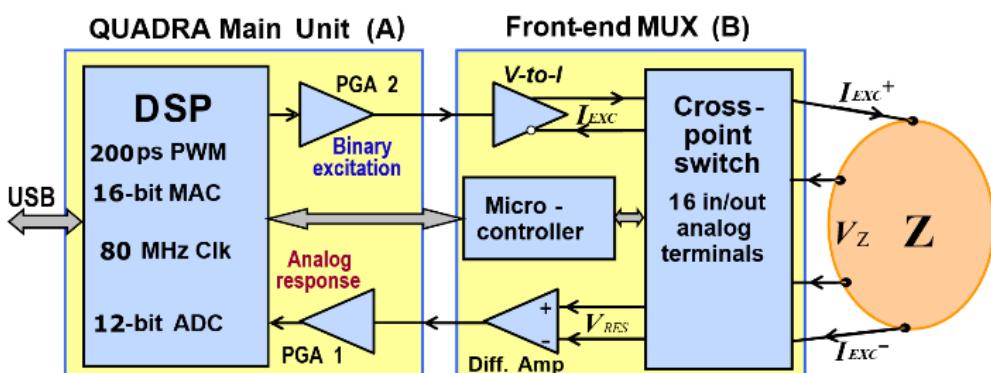


Figure 1: Structure of the spectro-tomography device – the base unit (A), and the developed multiplexing front-end (B)

switching goes on under control of the microcontroller in the front-end unit B, see fig.1. A photo in fig. 4 shows the spectro-tomography device developed in accordance with the structure in fig.1.

Commutation Procedure

Switching of excitation and response pick-up nodes is synchronized with applied excitation signal cycles after every 1 ms. Both, the excitation current I_{EXC} and response voltage V_{RES} are switched over hundreds of times during one tomography round, according to the used excitation and measurement pattern and the number of electrodes. See different patterns for example in [5, 6]. The total measurement time may reach several seconds or minutes. Therefore, minimizing of the switch over time is exceptionally important in the tomography of time-variant impedances.

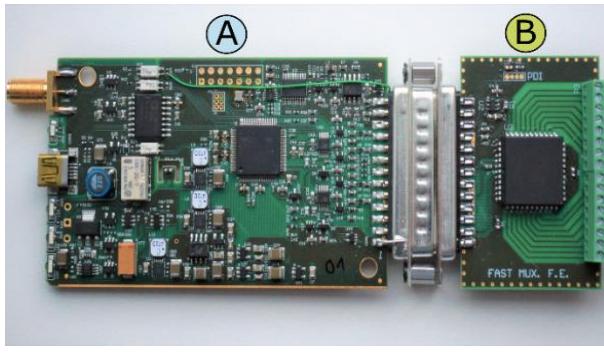


Figure 4: A photo of the prototyped spectro-tomography device containing the main digital processing unit (A), and a multiplexing front-end (B)

Shortening of the switching time is limited by at least two instrumentation factors: 1) ability of electronics to accomplish the switching process fast, and 2) capability to process the response signals at the highest possible speed. More important is the dependence on the inertia of bioimpedance to analyze. When switching over the excitation current, we cannot measure before the settling of voltage response. The main time constant of tissues can vary greatly. Our primary interest are cell suspensions that expresses characteristic α - and β -dispersions. The characteristic frequency of cell suspensions in α -region lies between 150 Hz to 1.5 kHz [7]. At this region, the time constant can reach 1 ms, at which the transient response takes 5 to 10 ms for the detecting of tiny changes

The electronics and signal processing algorithms of the developed spectroscopy device Quadra enables the signal processing in real time during the 1 ms excitation cycle. Because the switching moment corrupts the response during only a very short interval (takes a single or pair of microseconds), acquisition of the new response voltage takes 2 ms instead of 1 ms, ideally. Let us repeat here that the time interval, which is required for voltage acquisition after subsequent sampling of response can be short and is

not dependent on inertia of the bioimpedance. On the other hand, the time for settling of voltage after the switching of excitation current depends directly on the inertia of bioimpedance and takes significantly more time than the sampling of voltage response. By our practice, the transfer processes can take more than 1 ms and one current commutation step can last several milliseconds, for example, even 4 ms in our experiments.

Analog Circuitry for Measurement Signals

Fig. 5 depicts the analog part of the developed device [4]. The digital signal processor DSP (fig. 1) generates the binary sequence of pulses V_{EXC} (fig. 2) with the predetermined spectrum of 15 spectral lines (fig. 3) at the required frequencies. A voltage-to-current converter (V -to- I) converts the voltage to excitation current I_{EXC} with 1 mA amplitude (fig. 1) using a resistor R_{REF1} in the current feedback chain of operational amplifier (OpAmp), see fig. 5. Every single spectral component of the synthesized ones (fig. 3) has the RMS value of 0.25 mA.

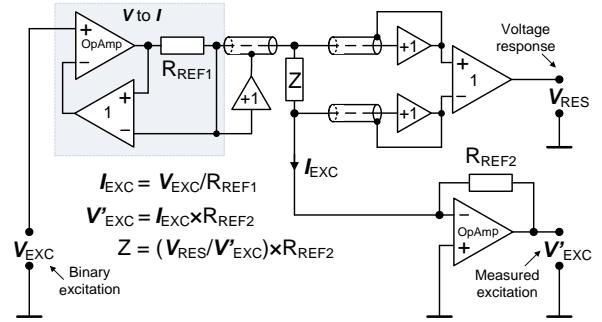


Figure 5: Analog part with a voltage to current converter (V -to- I), a circuit for pick-up the response voltage V_{RES} , and an excitation measurement circuit

Although the current converter operates with high quality at lower frequencies, its output impedance goes down to 10 k Ω at 1 MHz. The degradation takes place due to parasitic capacitances, mostly, but also from the lowering of amplification of the feed backed operational amplifier (OpAmp) in the V -to- I .

Due to this degradation, the excitation current I_{EXC} through the impedance Z is measured by the aid of current-to-voltage converter, containing an inverting operational amplifier (OpAmp) with feedback resistor R_{REF2} (fig. 5). The I_{EXC} measurement results in voltage V'_{EXC} . The response voltage V_{RES} comes from the impedance Z as a voltage drop caused by the excitation current I_{EXC} . The response V_{RES} is picked up by the aid of a unity gain differential amplifier with guarded inputs.

Bioimpedance spectro-tomographic measurements

In order to evaluate the performance of the new spectro-tomography device, we used 16 equally distributed electrodes in a tank to image a phantom (schematic in fig. 6). Each of the 16 pins of the multiplexer was

connected to one of the 16 electrodes in the tank and several tetrapolar impedance measurements were conducted through them. For the tetrapolar measurements, we applied an opposite excitation pattern and measured voltages serially between other electrodes. For example, when excitation was applied between electrodes 1-9, voltages were measured between electrodes 2-3, 2-4, ..., 2-16. In total, we obtained 16 excitation patterns and 13 voltage measurements for each, leading to 208 tetrapolar impedance measurements.

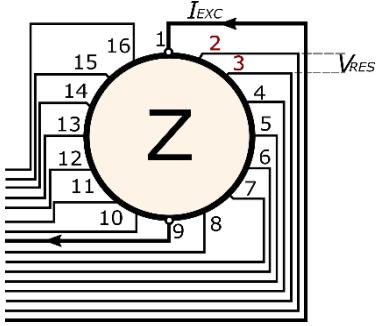


Figure 6: Connections of the measurement tank with impedance Z to multiplexing front-end

The tank (220 mm in diameter) was filled with saline solution with a concentration of 1ppt (a part per thousand). A vegetable (yellow beetroot) was cut into a triangular shape and placed in the middle of the tank (fig. 7(a)). The electrodes were bolt heads made of stainless steel and 6.6 mm in diameter. Before adding the vegetable into the saline solution, the tank was measured with only saline solution in it to obtain reference data for time-difference images.

Reconstruction of spectro-tomographic images

Images representing the conductivity change were reconstructed using an open source software EIDORS v3.9 (Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software) [8] in MATLAB R2016a (The MathWorks, Inc.). In addition to the measured impedance values, the minimum information one needs in the image reconstruction are the dimensions of the measured setup and the excitation and measurement pattern used. For computing the conductivity values in a finite element mesh approach, we applied a one step Gauss-Newton solver and a Laplacian smoothness prior with hyperparameter value of 0.005. A complete electrode model with contact impedance value 0.01Ω was used.

In difference mode electrical impedance tomography, the conductivity values are computed from two sets of data. Thus, they represent the change of the conductivities rather than the absolute conductivity values. In this paper, the images were reconstructed both in time-difference and frequency-difference mode. In time-difference, the data at certain frequency is compared to a reference data from a different time point but equal frequency. In frequency-

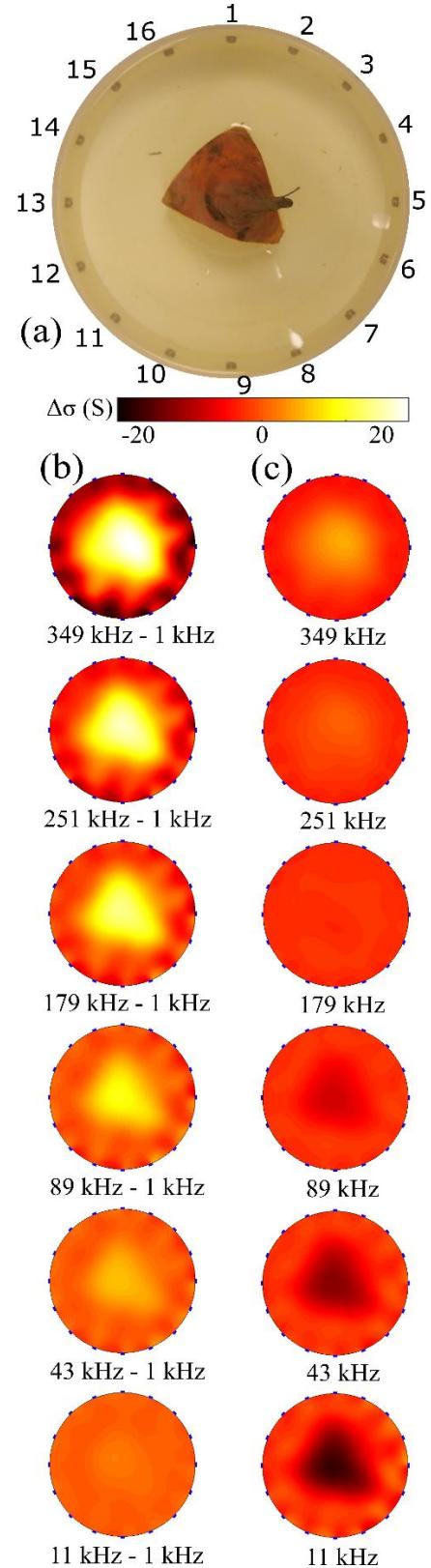


Figure 7: Reconstructed images of an experimental phantom measurement in a 16-electrode tank; a photograph of the measured tank with triangular vegetable in saline solution (a), frequency-difference (b) and time-difference (c) reconstructions. The conductivity change depends on the applied frequency.

difference, the data at certain frequency is compared with the same time point but with different frequency.

Results

The frequency-difference and time-difference reconstructions of the triangular vegetable are shown in fig. 7 (b, c). The frequency of the data ranged from 11 kHz to 349 kHz in both reconstruction modes. The reference data was chosen to be 1 kHz in the frequency-difference images. Thus, these images represent the change of conductivity compared to the conductivity at 1 kHz (fig. 7 (b)). On the other hand, time-difference images represent the change of conductivity due to inserting the vegetable into saline solution.

Both reconstruction modes indicate that the conductivity of the vegetable increased as the applied frequency increased. This change becomes visible at 43 kHz and above in the frequency-difference images. According to time-difference images, the vegetable was more resistive than the saline solution until 89 kHz. At 179 kHz, the vegetable was as conductive as saline solution (no change was detected), but above this, the vegetable became more conductive than the saline solution. These results are in accordance with [9], for example.

Discussion

The new bioimpedance spectro-tomography device has been presented and demonstrated to work at frequencies from 1 kHz to 349 kHz. Reconstructed images met expectations: conductivity of the vegetable increased as the applied frequency increased, and both the shape and location of the phantom were correct. The excitation pattern and the relatively small number of electrodes used limit the resolution of the results. For enhanced image resolution, excitation patterns including, for example, skip-3 pattern could provide more accuracy to the results. For including the 3D spectro-tomography of time varying impedances, different methods for further minimization of measuring time will become actual.

Conclusions

The presented spectro-tomography device provides a fast and effective tool for bioimpedance applications. Binary excitation enables to make instrumentation part simple and power efficient. In perspective, both, battery based power supply and wireless communication make possible to isolate the device electrically and minimize accompanying interference.

References

- [1] Y. Yang and J. Jia. A multi-frequency electrical impedance tomography system for real-time 2D and 3D imaging. *Rev. Sci. Instr.* 88, 085110, 2017, DOI: 10.1063/1.4999359.
- [2] M. Rist *et al.* Modular System for Spectral Analysis of Time-Variant Impedances. In I. Laskovic, D. Vasic (eds.), *IFMBE Proc.* 45, pp 858-861. Springer Switzerland, 2015.
- [3] M. Min, J. Ojarand *et al.* Binary signals in impedance spectroscopy. In *IEEE EMBS Soc. EMB Conf.* 2012, pp 134-137. IEEE, Hoboken, NJ, 2012.
- [4] M. Rist. Principles for the Design of Impedance Spectroscopy Devices for Identification of Dynamic Bio-Systems. PhD thesis, Tallinn University of Technology, Tallinn, Estonia, 2018.
- [5] P. Kauppinen *et al.* Sensitivity distribution visualizations of impedance tomography measurement strategies. *Int. J. Bioelectromagn.* 8, 1-9, 2006.
- [6] M. Lehti-Polojärvi and O. Koskela *et al.* Rotational electrical impedance tomography using electrodes with limited surface coverage provides window for multimodal sensing. *Meas. Sci. Technol.* 29 025401, 2018, DOI: 10.1088/1361-6501/aa97f1.
- [7] S. Grimnes and O. G. Martinsen, Ch. 4 Passive Tissue Electrical Properties (p. 93-95), in: *Bioimpedance and Bioelectricity Basics*, 3rd ed., Academic Press (Elsevier), 2015.
- [8] A. Adler and WRB Lionheart. Uses and abuses of EIDORS: an extensible software base for EIT. *Physiol. Meas.* 27(5): 25-42, 2006.
- [9] S. Ahn *et al.* Frequency-difference electrical impedance tomography: Phantom imaging experiments. *J. Phys.: Conf. Ser.* 224(1), 012152, 2010, DOI: 10.1088/1742-6596/224/1/012152.

Acknowledgements

Image reconstruction part was supported by Jane and Aatos Erkko Foundation (Finland) and by Business Finland Human Spare Part Program. The authors would like to thank Olli Koskela (Tampere University of Technology) and Aku Seppänen (University of Eastern Finland) for their advice in the image reconstruction. The institutional grant IUT1911 of Estonian Research Council and Estonian IT Center of Excellence EXCITE supported the development of instrumentation part.