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Two-Channel Bioimpedance Monitor for Impedance Cardiography

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***Abstract*—In this paper we introduce our conception of a two-channel bioimpedance monitor for the impedance cardiography. We describe the design of a homemade device which is based on a direct digital synthesizer and a digital down converter. This solution enables us to obtain a high-quality bioimpedance signal, which can be used for computing the cardiac output beat per beat. It further enables us to analyze impedance phase changes beat per bear. Our device allows simultaneous measuring of complex impedance in two arbitrary directions on human/animal body without any interference between channels. The setting of the main parameters of the measurement like the amplitude and the frequency of the measurement current depends on the user.**

I. Introduction

BIOIMPEDANCE measurement for cardiac system analysis was introduced by Kubicek more than 40 years ago [1]. The main advantage is the noninvasive process of this measurement.

The main principle of the bioimpedance measurement is based on applying a weak electrical current to patient´s body and scanning the induced electrical voltage. Bioimpedance techniques in medicine have many applications from skin resistance measurement through cardiac system analysis to impedance tomography [2].

The impedance cardiography (ICG) measures impedance changes in the thorax to calculate the stroke volume or the cardiac output respectively as the final quantity. The evaluation of the stroke volume from the bioimpedance signal went through its evolution from the former Kubicek equation, through Sramek equation and finally to Bernstein equation [3], and it seems to be continued. Lots of studies show us that ICG has similar accuracy and reproducibility like other methods for the cardiac output evaluation, e.g. the invasive and expensive thermodilution, echocardiography requiring high skilled and experienced operator [4], [5]. The essential attribute of ICG for our purpose is its mentioned noninvasive type. We concentrate on analyzing the cardiovascular system properties and developing new noninvasive diagnosis methods [6]. For this purpose we do a complex measurement, and the stroke volume computed from ICG is one of the most important parameters which are used together with other biological signals (ECG, breathing, blood pressure, phonocardiogram, etc.) to evaluate the state of the cardiovascular system. Because of the experimental and research type of our measurement and thus the necessity of setting all parameters of the measurement arbitrary, we decided to build a homemade two-channel bioimpedance monitor which enables us to have all the measurement parameters and further signal evaluation (continuous stroke volume and/or cardiac output beat per beat) fully under our control.

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II. Methods

The thorax electrical impedance is measured by the standard four-pole method which is less sensitive to the electrical property of the electrodes and their coupling with the skin. In the first channel we use the current source for the outer two electrodes on the neck and the groin. The voltage is monitored by the inner electrode pair placed in the neighborhood of the clavicle and under the rib cage. All electrodes are placed on the left side of the thorax. The second channel is applied perpendicularly – current electrodes over the shoulders and voltage is monitored on the chest – all four electrodes are placed in one horizontal line. The aim is to monitor the cardiac output into the aorta and the pulmonary artery [7] simultaneously. In general each channel can be placed on arbitrary position on the body. E.g., to study the arterial system elasticity, one channel can be placed on the thorax and the second one on an upper or lower limb to evaluate the shape and time relations of the blood flow in the aorta and in the limb (pulse wave).

Measuring of more than one channel brings up the problem of their separation. We have chosen the so called frequency multiplex which means that each channel i has its own carrier frequency f_{ci}. The frequencies of all the channels should be as close to each other as possible to minimize frequency dependence of all the channels. The other requirement of the bioimpedance system is a high dynamic range of the whole device because of very small changes of the bioimpedance induced by the heart activity with respect to the overall static bioimpedance of the body and the breathing influence impedance contribution.

The main idea is the usage of a couple of digital transmitters and receivers which are controlled by a common frequency standard. Then a coherent signal demodulation is enabled. This solution is able to fulfill both demands: the narrow band signal processing and the high dynamic range. The block diagram of the proposed device is shown in Fig 1. The bioimpedance monitor consists of three

main parts: a digital measurement unit (DMU), an analogue interface (AI) and a standard personal computer (PC). The whole system is controlled by a special software in the PC. DMU generates measurement carrier frequencies for both channels. Both DR and DDS are controlled by the digital signal processor (DSP) which also communicates with the hosting PC. The CLK block is the source of the common clock signal for all digital parts of the DMU. The exact digital control of DDS and DS parts together with CLK guarantees the phase coherence of the whole device. An analogue interface is used for connecting the DMU input

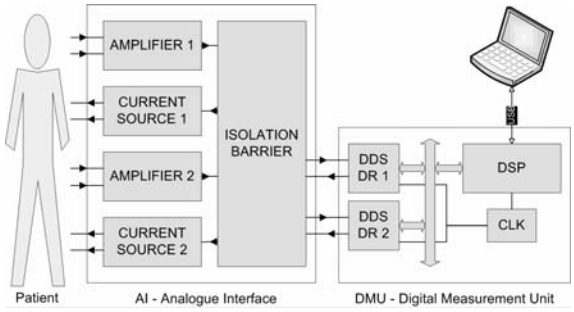

Fig. 1. Block diagram of the two-channel bioimpedance monitor.

and output signals to the patient.

The crucial part of DMU is the DDS+DR block. This consists of a direct digital synthesizer (DDR) and a digital receiver (DR). This solution was chosen for its frequency accuracy and stability. The principle block diagram of the DDS+DR block is shown in Fig. 2. The output carrier frequency is generated digitally in the digital synthesizer of the output part and an analogue signal is obtained in the digital to analogue converter (DAC). Digitalizing of the measured bioimpedance signal is done by an analogue to digital converter (ADC) followed by a digital down converter – the input part (DR). The digital down converter

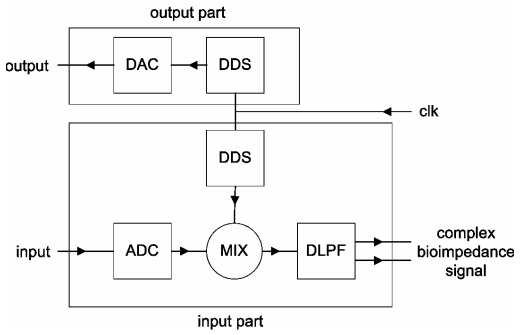

Fig. 2. Principle diagram of the DDS+DR block.

consists of the direct digital synthesizer which generates the identical carrier frequency as in the output part. The digital input data are thus coherently demodulated in the digital mixer which shifts the selected frequency band to the region with zero frequency in the center. A coherent demodulation is also a prerequisite for obtaining a continuous phase of the bioimpedance signal. The output of the digital mixer is a complex signal that consists of real and imaginary components. The digital low pass filter (DLPF) block consists of a pair of digital decimation low pass filters which reduce the sampling frequency and the frequency band of the output complex signal. DR parts use the high oversampling principle and this has major influence on a high signal to noise ratio of the ICG signal and a good separation of both channels. We achieved these DMU parameters: DDS – output frequency 0.01-120 MHz, narrowband SFDR (5 kHz) 86 dB; DR – input frequency bandwidth 0.01-130 MHz, dynamic range 148 dBFS/Hz, jitter lower than 0.5 ps [8]. The carrier frequency resolution for both DDS and DR is 0.01 Hz. The analogue interface limits the bandwidth up to 120 kHz. The output sampling frequency can be set up to 10 kHz (we use 500 Hz for most applications). Both parameters are reasonable for the ICG purpose. The measurement current can be set up to 5 mA RMS.

A PC-type computer obtains - from the DMU via USB - digital data representing the complex valued voltage on sensing electrodes. The magnitude and the phase or the real and imaginary parts of the bioimpedance signal are calculated by means of Ohm's law. From this bioimpedance signal the desired quantity is calculated, e.g. the stroke volume or the cardiac output [1], [3]. Other signals can be calculated as well, e.g. the breathing signal can be obtained by simple band pass filtering (0.05-0.5 Hz) of the bioimpedance data.

III. Experimental Results

The device was built and tested successfully. An example of a raw bioimpedance signal is shown in Fig. 3 and Fig. 4.

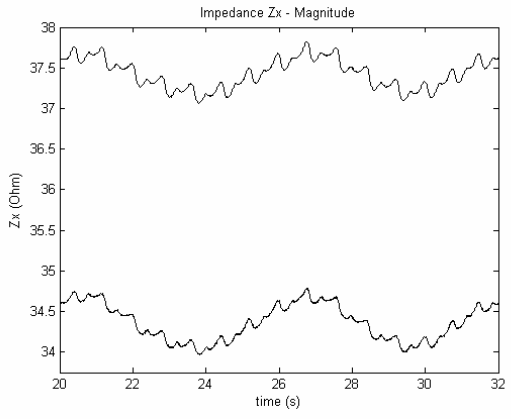

Fig. 3. A magnitude of the bioimpedance of the thorax. The upper curve represents the aorta direction and lower represents the pulmonary aorta direction.

The curves depict the absolute value and the phase of the bioimpedance signal in vertical (aorta) and horizontal

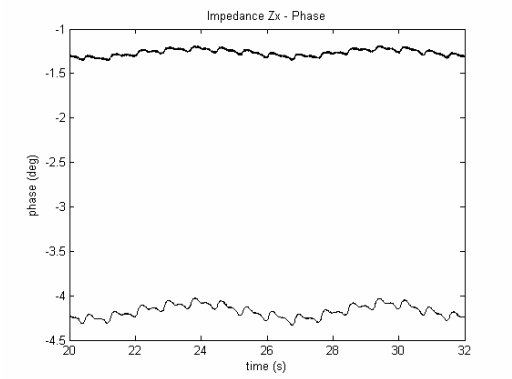

Fig. 4. A phase of the bioimpedance of the thorax. The upper curve represents the pulmonary aorta direction and lower represents the aorta direction.

(pulmonary aorta) directions of the thorax respectively. In both figures the raw data include the static part of the body impedance and the variable part induced by breathing and by the cardiac activity. In both cases the patient was resting in supine position. Fig. 5 shows an example of a processed bioimpedance signal together with continuous blood pressure and ECG for several beats. The bioimpedance signal in this figure is in the pass band 0.3-12 Hz. Fig. 6 shows an example of a part of a measurement of a patient on a tilt table. The stroke volume was computed as the integral of the absolute value of –dZx/dt in one heart beat interval (R-R interval). A noticeable change of the cardiac output and the stroke volume signals is evident in the middle of the graph in the place marked with a vertical line. This change is caused by moving the patient from the supine position into tilt position.

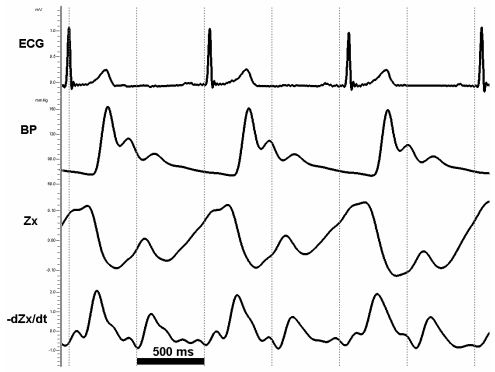

Fig. 5. A detail of the measured bioimpedace together with blood pressure and ECG. ECG – electrocardiogram; BP – blood pressure; Zx – filtered bioimpedance signal and –dZx/dt – negative derivative of the bioimpednace signal.

IV. Discussion and Conclusion

The two channel bioimpedance monitor for the impedance cardiography was designed, made and tested successfully. The device is used for research purposes. The complex output two-channel signals enable the beat per beat analysis in two independent channels simultaneously. The absolute value and the phase or the real and imaginary values can be used for further analysis. A clinical asset of the two channel measurement is under investigation in cooperation with St. Anne's Faculty Hospital in Brno, Czech Republic.

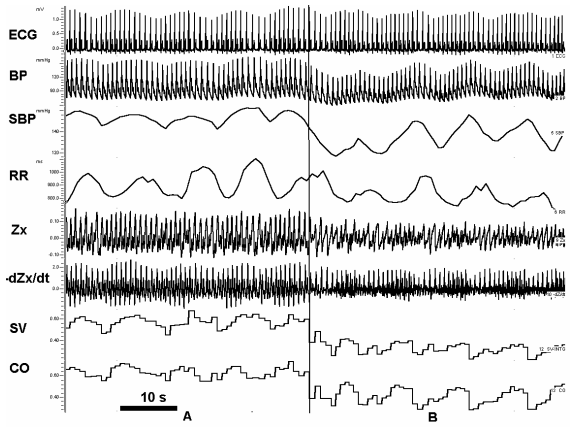

Fig. 6. Bioimpedance measured together with other signals on a tilt table. ECG – electrocardiogram; BP – blood pressure; SBP – systolic blood pressure; RR – RR interval; Zx – filtered bioimpedance signal; –dZx/dt – negative derivative of bioimpednace signal; SV – stroke volume and CO – cardiac output. A – supine position, B – head up tilt 75 degree.

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