33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

AD5933-Based Electrical Bioimpedance Spectrometer. Towards Textile-Enabled Applications

J. Ferreira, *Student Member IEEE,* F. Seoane, *Member IEEE,* and K. Lindecrantz, *Member IEEE.*

***Abstract*— Advances on System-On-Chip and Textile technology allows the development of Textile-enabled measurement instrumentation. Textile Electrodes (Textrodes) have been proven reliable for performing Electrical Bioimpedance Spectroscopy (EBIS) measurements, and the availability of a integrated circuit impedance spectrometer, the AD5933, has allowed the implementation of small size EBIS spectrometers.**

In this work an AD5933-based spectrometer has been implemented, and its performance on 2R1C circuits and for tetrapolar total right side EBIS measurements has been compared against the commercially available spectrometer SFB7. The study has been focused on the working upper frequency range and the estimation of the Cole parameters required for assessment of body fluid distribution: R_0 and R_∞. The results indicate that AD5933-based spectrometer implemented in this work can perform accurate impedance measurements well above the upper limits recommended in the datasheet. The AD5933-EBIS presents a good performance compared with the SFB7 on the 2R1C circuit and the total right side measurements, showing a smaller error in the resistance spectrum and small deviation error in the reactance when measuring over 270 kHz. The comparison on the Cole parameters estimation obtained with the SFB7 and the AD5933-based spectrometer exhibit a difference below 1% for the estimation of R_0 and R_∞. Consequently the overall measurement performance shown by the implemented AD5933-based spectrometer suggests its feasible use for EBIS measurements using dry Textrodes. This is of special relevance for the proliferation of EBI-based personalized health monitoring systems for patients that require to monitor the distribution of body fluids, like in dialysis.

I. INTRODUCTION

Technological improvements in System-on-Chip technology have enabled the integration of complex functional systems into a single integrated circuit. As a result a complete impedance spectrometer is available on a single integrated circuit: AD5933 manufactured by Analog Devices [1]. Its availability in combination with a 4-Electrode Analog Front End (4E-AFE) [2] has allowed the development of a complete Electrical Bioimpedance Spectrometer (EBIS). The performance of the AD5933-based EBIS has been tested on electrical 2R1C-circuits for several Electrical Bioimpedance (EBI) applications [3], validating its potential use on EBI applications like Body Composition Assessment (BCA).

Recent developments in conductive textile fabrics and electrode technology have allowed the implementation of Textile electrodes (Textrodes) garments for EBI-based measurements for BCA [4-5] and cardiovascular monitoring [6].

The BCA parameters indicating the amount of Extra-Cellular (ECF), Intra-Cellular (ICF) and Total Body Fluid (TBF) [7] are obtained from the estimation of the resistance value at DC and infinite frequency, known as Cole parameters R_0 and R_∞. The broader the frequency range of the obtained EBI measurement spectrum, the better the accuracy of the estimations of the Cole parameters will be. Therefore the frequency limits of the EBI measurement play an important role in the correct estimation of the BCA parameters.

According to the datasheet [1], the AD5933 spectrometer recommended frequency analysis is from 1 to 100 kHz with a system accuracy below 0.5%, but in reality the device allows to perform impedance measurements up to 500 kHz. The availability of such EBI spectrometer together with the proper textrode garment would allow the implementation of BCA monitoring systems for home applications [8].

In this work, the measurement performance of a custom made AD5933-based EBI spectrometer using dry Textrodes is studied, with typical experimental EBI measurements for BCA from the point of view of the estimation of R_0 and R_∞ and with special attention to the upper frequency limit. The work is based in a comparative study between the AD5933-based EBI spectrometer and a commercially available spectrometer: the ImpediMed SFB7.

II. MATERIALS AND METHODS

A. EBI Spectrometers

Two EBI spectrometers have been used in this work: the ImpediMed SFB7 and a custom made AD5933-EBIS.

The SFB7 [9] performs tetrapolar measurements in the frequency range from 4 kHz to 1000 kHz, and it has been used as a golden standard.

The AD5933-EBIS is based the AD5933 Impedance

Manuscript received April 15, 2011.

J. Ferreira is with the School of Engineering at the University of Borås, 501 90 SWEDEN and the School of Technology and Health at Royal Institute of Technology, SE-141 52 Huddinge, SWEDEN (javier.ferreira@hb.se)

F. Seoane is with the School of Engineering at the University of Borås, 501 90 SWEDEN and the School of Technology and Health at Royal Institute of Technology, SE-141 52 Huddinge, SWEDEN. (fernando.seoane@hb.se).

K Lindecrantz is with the School of Technology and Health at Royal Institute of Technology, SE-141 52 Huddinge, SWEDEN. (kaj.lindecrantz@sth.kth.se)

978-1-4244-4122-8/11/$26.00 ©2011 IEEE

Fig.1 Textrode garment prototype placement.

Network Analyzer as impedance core, and performs also tetrapolar measurements implementing the 4E-AFE introduced in [2] . The upper frequency limit was incremented up to 450 kHz just by programming the AD5933 registers to do so. The AD5933-based EBIS is battery driven and uses Bluetooth technology to control and transfer the measurements to a PC station.

A. Measurement Textrodes

A custom designed Textrode garment, see Fig.1, has been used to perform Total Right Side EBI measurements [10]. The textrode is based on two pieces: one for the hand-wrist and other for the foot-ankle both incorporating two separate conductive textile areas used as electrodes for current injection and voltage sensing.

The garment has Velcro fasteners and snap-button connectors. The outer layer is made of synthetic wrap knitted fabric and an intermediate foam layer assures good skin-electrode contact. The inner surface is made of conductive Shieldex® Fabric P130+B. The Shieldex® fabric is a two dimension stretchable conductive fabric based on Silver Plated (99% pure silver) and with a raw material constitution of 78% Polyamide and 22% Elastomer.

B. 2R1C and EBIS Measurements

Using both spectrometers EBIS measurements were taken on a 2R1C circuit dummy, and Total Right Side (TRS) [11] on three healthy subjects lying supine in a resting state. The 2R1C circuit model was implemented with a resistor of 1.21 kΩ in series with a 1 nF capacitor, both in parallel with a resistor of 604 Ω, all components with a 0.1% precision. A set of 30 complex EBI spectroscopy measurements were taken for each subject with the textrode garment. In the case of the 2R1C circuit, 20 measurements were taken.

C. Spectrum Analysis and Cole parameters estimation

The complex impedance spectra have been compared in the frequency range 5 – 450 kHz, for both circuit and TRS measurements. In addition the Cole parameters, R_0, R_∞ and f_C, have been estimated from the TRS EBI spectra using the three frequency ranges: 5-100 kHz, 5-200 kHz and 5-450 kHz. The estimation of the Cole parameters have been estimated using Impedimed Bioimp Software, the Cole parameter estimation has been performed with the TD compensation option disabled.

III. RESULTS

A. 2R1C Circuit Measurements

The average resistance and reactance spectra from the 2R1C circuit measurements are plotted in Fig. 2. Both devices present a good performance, but the reactance spectrum obtained with the AD5933-EBIS exhibits a slight deviation at high frequencies.

The Absolute error for the Resistance and the Reactance spectra is shown in Fig. 3 with a doted and cross marker line for the AD5933-EBIS and SFB7 respectively. The AD5933-EBIS presents a lower error value in the resistance spectra compared to the SFB7. In the Reactance plot, the AD5933-EBIS presents an error greater than 5% above 270 kHz approximately; while SFB7 has an error lower than 4% for

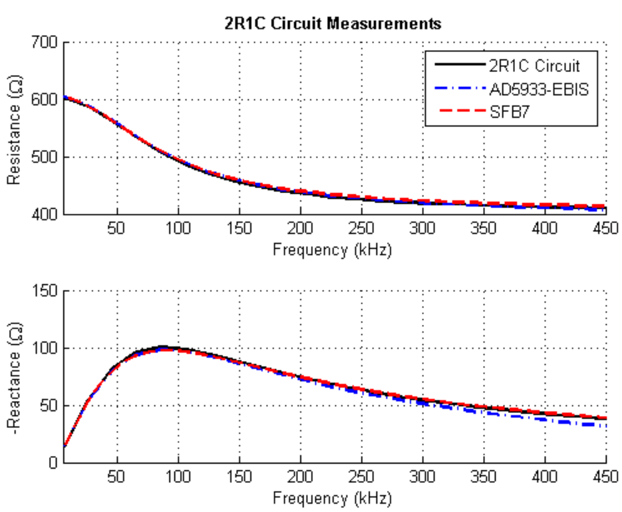

Fig.2 Impedance Measurements on 2R1C circuit with SFB7

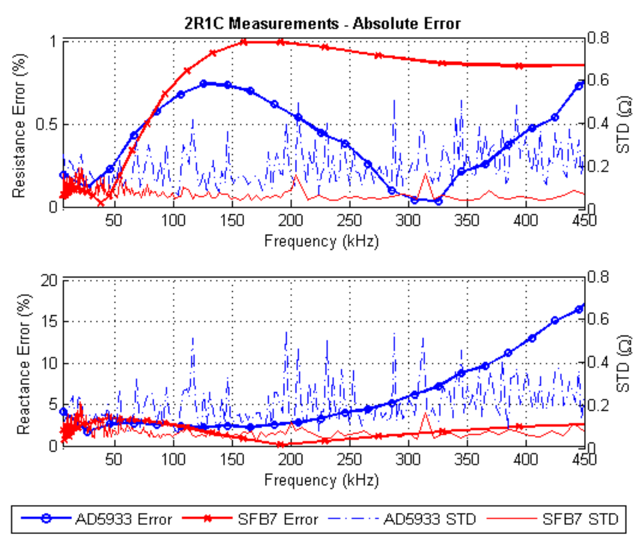

Fig.3 Absolute Error and STD for 2R1C circuit measurements.

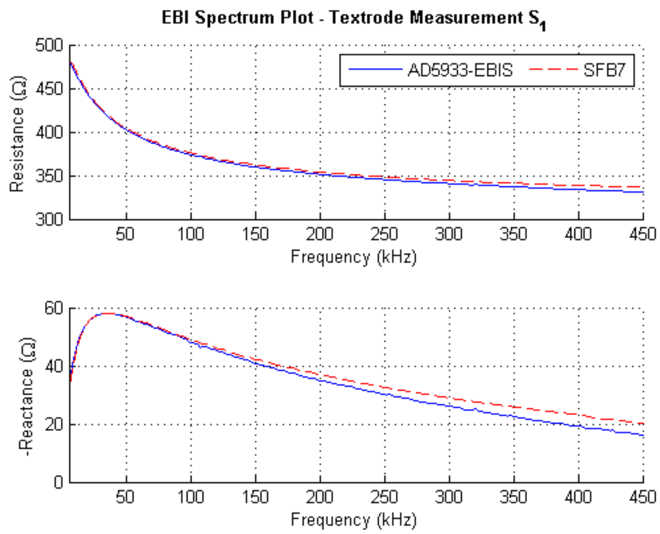

Fig. 4 Resistance and Reactance TRS spectrum plots for Subject 1 with SFB7 and AD5933 EBIS.

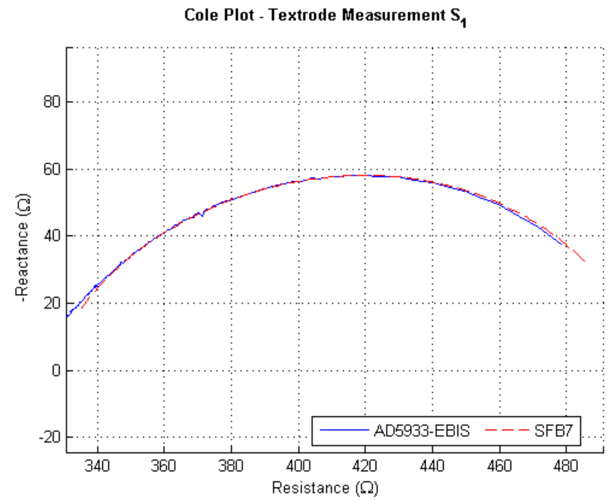

Fig.5 Impedance Plot for EBI TRS measurement on Subject 1.

the complete frequency range. In the same figure the Standard Deviation (STD) for the 2R1C measurements is shown for both devices, the SFB7 presents lower STD compared with the AD5933-EBIS. In both cases the STD stays below 0.5 Ω.

B. Spectral Measurement

The complex EBIS measurements obtained with both spectrometers were very similar for the three subjects, exhibiting the same underestimation on the reactance spectrum at high frequencies as observed in the 2R1C circuit measurements. The averaged resistance and reactance spectrum for Subject 1 is shown in the Fig. 4. The resistance spectrum presents a slight difference at frequencies above 200 kHz. In the case of the reactance spectrum the differences is more noticeable and increasing with the frequency.

The impedance plot for EBIS measurements Subject 1 is shown in Fig. 5. The impedance plots obtained with both devices are nearly similar, making difficult to trace some difference between them.

C. Cole Parameter Estimation

The estimated values for the Cole parameters are shown in Table I. This table provides the average values for the Cole parameters estimations obtained with the BioImp Software from the EBI measurement performed on each subject with both spectrometers. The values estimated from the measurements taken with both spectrometers in the frequencies ranges of 5-100 kHz and 5-200 kHz are very similar. In Table II it is possible to observe the mean difference among the three subjects for each of the parameters, and for each of the three frequency ranges. Notice that for R_0 *and* R_∞ the difference is kept below 1.2%, in the frequency range of 5-450 kHz, the difference on the Cole parameters it is slightly larger but it is still relatively very small

In Table I and Table II it is possible to observe that the deviation produced on the estimation of characteristic frequency, f_C, it is slightly larger than in the cases for R_0 and R_∞.

Table III shows the Mean Absolute Deviation between the estimation of the Cole parameter obtained with the SFB7 using the 5-450 kHz frequency range and the value for the Cole parameters estimated from the measurements taken with the AD5933-EBIS for the 3 frequency ranges. In the table it is possible to observe that the difference for R_0 and R_∞ is smaller than 1%.

IV. Discussion

The close resemblance between the impedance spectra obtained from the 2R1C circuit indicate that the AD5933-EBIS can indeed perform accurate impedance measurement well above other upper limits previously reported, 100 kHz

TABLE I
COLE PARAMETERS ESTIMATION

Frequency (kHz)	Device	R_0 (Ω)			R_∞ (Ω)			f_C (kHz)		
		S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3
5-100	*AD5933*	510,4	566,9	546,3	325,0	399,5	338,7	35,0	37,7	25,0
	SFB7	509,6	562,8	546,4	328,2	402,4	344,9	35,7	38,0	25,5
5-200	*AD5933*	511,8	567,9	547,8	322,8	397,6	337,0	35,2	37,9	25,2
	SFB7	511,1	564,0	547,7	324,8	399,4	342,7	36,5	38,9	25,7
5-450	*AD5933*	514,2	568,8	549,5	320,9	396,8	336,1	37,4	40,5	28,4
	SFB7	511,9	564,5	547,9	323,3	398,4	342,4	36,2	38,3	25,5

TABLE II
TOTAL MEAN RELATIVE DIFFERENCE

Frequency Range	R_0 (%)	R_∞ (%)	f_C (%)
5-100 kHz	0,29	1,18	1,55
5-200 kHz	0,29	0,92	2,67
5-450 kHz	0,49	0,99	6,76

TABLE III
TOTAL MEAN RELATIVE DIFFERENCE FOR THE AD5933-EBIS

Frequency Range	R_0 (%)	R_∞ (%)	f_C (%)
5-100 kHz	0,06	0,10	2,33
5-200 kHz	0,19	0,64	1,71
5-450 kHz	0,49	0,99	6,76

in [2-3] and 200 kHz in [12]. The deviation in the reactance spectrum observed with increasing frequency might be related with that fact the load for the initial calibration was just a resistance, among other factors. A deeper study about the elements influencing in the accuracy and preciseness of the AD5933 is being done.

Despite the clear deviation observed in the reactance at high frequencies, the Cole parameter estimation performed from EBIS data measured up to 450 kHz produce very similar values for R_0 and R_∞ to those estimated from the EBIS measurement performed with the SFB7. This is due to the fact that the semicircular plot produced by the EBIS measurements taken with both spectrometers are almost identical, and since the curve fitting to the Cole function implemented by the Bioimp software fits the EBIS data in the impedance plane, it is expected that similar impedance plots will produce similar values for R0 and R∞. The estimation of the Cole parameters depend on the curve fitting approach implemented. Since the resistance spectrum obtained with spectrometers are very similar, the use of other estimation algorithms based in the resistance spectrum only, such as the one in [13], would also produce precise estimations for R_0 and R_∞.

Since the estimation of the body fluid distribution from EBIS data currently depend only on the estimates of R_0 and R_∞ [7], it is very likely that the AD5933-EBIS spectrometer in combination with the Textrode garment would be useful for BCA applications. A clinical study comparing the performance of several commercial EBIS meters with the AD5933-EBIS is schedule to be performed shortly.

V. Conclusions

The results obtained show the feasibility to obtain accurate TRS EBIS measurements using the custom made AD5933-EBIS with dry Textrodes for Cole parameter and BCA estimation.

The AD5933 EBIS presents a good performance compared with the SFB7 on the 2R1C measurements, showing a smaller error in the resistance spectrum measurement but a noticeable error in the reactance spectrum at frequencies above 270 kHz. On the other hand, the difference observed in the estimation of the Cole parameters, R_0 and R_∞ using the AD5933 EBIS is below 1% when compared with the values estimated from a commercial EBIS meter like the SFB7.

The availability of Textrode garments and reduced size spectrometers like the AD5933-EBIS used in this work will enable the implementation of EBI-based personalized health monitoring systems for body fluid distribution. Such systems could play an important role improving the quality life of chronic kidney disease patients requiring dialysis for example.

References

[1] A. Devices. "AD5933 Datasheet Document," http://www.analog.com/static/imported-files/data_sheets/AD5933.pdf.

[2] F. Seoane, J. Ferreira, J. J. Sanchéz *et al.*, "Analog Front-End Enables Electrical Impedance Spectroscopy System On-Chip for Biomedical Applications," *Physiol. Meas.* , vol. 29 pp. S267-S278, 2008.

[3] J. Ferreira, F. Seoane, A. Ansede Peña *et al.*, "AD5933-Based Spectrometer for Electrical Bioimpedance Applications," in International Conference on Electrical Bioimpedance, Gainesville, Florida, 2010.

[4] J. C. Marquez, J. Ferreira, F. Seoane *et al.*, "Textile Electrode Straps for Wrist-to-Ankle Bioimpedance Measurements for Body Composition Analysis. Initial Validation & Experimental Results," in IEEE EMBC 2010, Buenos Aires, Argentina, 2010.

[5] J. C. Marquez, F. Seoane, E. Välimäki *et al.*, "Comparison of Dry-Textile Electrodes for Electrical Bioimpedance Spectroscopy Measurements.," in ICEBI2010, Gainesville, 2010.

[6] J. Muehlsteff, O. Such, and R. Willmann, "The Role of Technology for Non-Invasive Cardiovascular Monitoring in the Future Exemplified," *World Congress on Medical Physics and Biomedical Engineering, September 7 - 12, 2009, Munich, Germany*, pp. 388-391, 2009.

[7] M. Y. Jaffrin, and H. Morel, "Body fluid volumes measurements by impedance: A review of bioimpedance spectroscopy (BIS) and bioimpedance analysis (BIA) methods," *Medical Engineering & Physics,* vol. 30, no. 10, pp. 1257-1269, 2008.

[8] F. Zhu, G. Wystrychowski, T. Kitzler *et al.*, "Application of bioimpedance techniques to peritoneal dialysis," *Contrib Nephrol,* vol. 150, pp. 119-28, 2006.

[9] "Impedimed SFB7 - Home Web page," 2011-06-15; http://www.impedimed.com/products/sfb7-for-body-composition/sfb7-for-europe.htm.

[10] J. C. Marquez, and F. Seoane, "Textrode Garment for Bioimpedance Measurements. Experimental Results for Body Composition Analysis," *To be submitted in 2011*, 2011.

[11] U. G. Kyle, I. Bosaeus, A. D. De Lorenzo *et al.*, "Bioelectrical impedance analysis—part II: utilization in clinical practice," *Clinical nutrition (Edinburgh, Scotland),* vol. 23, no. 6, pp. 1430-1453, 2004.

[12] P. Bogonez-Franco, and et al., "Performance of an implantable impedance spectroscopy monitor using ZigBee," *Journal of Physics: Conference Series,* vol. 224, no. 1, pp. 012163.

[13] D. Ayllon, F. Seoane, and R. Gil-Pita, "Cole equation and parameter estimation from electrical bioimpedance spectroscopy measurements - A comparative study." pp. 3779-3782.