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Research paper

A new modular semi-parallel EIT system for medical application

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ABSTRACT

A modular semi-parallel EIT data acquisition system (SJTU Mk-1) for medical application is newly developed. It consists of one control module and an expandable number of independent frontend modules. The control module generates stimulating signals, intermediates the communication between remote PC and frontends, and synchronize frontends during parallel data acquisition. All frontend modules are closely and symmetrically connected to electrode sensing array, so the length of signal traces can be minimized for better measurement accuracy at higher frequencies. The system can spectrum impedance from 1 kHz to 1 MHz which covers the majority frequency range of medical impedance investigations. The amplitudes of stimulating currents are limited to 0.4 mA with built-in alarm of abnormal current on each frontend module for extra safety protection. Transformers and optoelectronic couplers are used to isolate the human body under test from mains power supply and geological ground. The developed EIT Data Acquisition System (DAS) is natively safe and suitable for medical applications. To maximize number of independent measurement for better spatial resolution of reconstructed image, the sensing array is implemented with compound electrodes. System performance tests at excitation current less than 0.5 mA show that, the Signal-to-Noise Ratio (SNR) of transfer impedance is higher than 70 dB, the amplitude and phase measurement repeatability are better than 0.6% and 1° respectively. Initial phantom experiments further demonstrate the imaging capability of the developed EIT DAS for medical application.

1. Introduction

Electrical Impedance Tomography (EIT) is a kind of non-invasive functional imaging technology to diagnose/monitor patients by measuring bioimpedances via externally wore electrode sensing array [1]. Benefited from low cost, fast imaging speed, no radiation hazard and high-sensitivity to functional change or biological activity of tissue, EIT is the only known imaging modality suitable for continuously monitoring lung function on bedside [2,3]. Medical EIT has also been actively investigated for pathological examination of malignant tissues like breast cancer [4,5], monitoring the bladder fullness [6], imaging neuronal depolarization in the brain [7], etc., which shows the prosperous of EIT research.

Although some novel integrated circuit chips have been commercialized in recent years for impedance measurement which is very convenient for developing wearable instruments, but they are generally for lower frequency application only. For example, AD5933/5934 from Analog Devices were first released in 2005, is for impedance measurement up to 100 kHz. AFE4300 from Texas Instruments is a very comprehensive one with bandwidth up to 250 kHz, but its internal integrated signal generator has only 6 bits of Digital to Analog Converter (DAC) which may lead to instability of the impedance measurement.

As for medical EIT, there are still physiological properties of tissue remain unknown. The intracellular physiological property can only be observed at high-frequency range [1]. Research at higher frequencies is still necessary and may actually be beneficiary or even has advantage to reveal new phenomenon. Development of broadband high performance DAS system is one important direction of EIT research.

If the EIT systems are classified according to their structure, we can see that many EIT systems including Sheffield Mk3.5 EIT/EIS system [8], UCLH Mk 2.5 [9], and some other systems [10,11] at the early EIT research, are all serial systems with only one set of stimulating sources and one channel of voltmeters. This kind of system is relative simple and has low cost. Analog multiplexers are used to sequentially switch the stimulating signals and voltmeters to

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different set of excitation electrodes and measurement electrodes. The parasitic capacitances of multiplexers and cables are major error sources when the measurement frequency is 250 kHz and above [12]. The serial EIT systems generally measure impedances at 200 kHz and below.

To overcome the parasitic capacitance affects, despite the significant complexity [12], a few research groups have implemented multiple stimulators and voltmeters fully parallel across all excitation channels and measurement channels, therefore no multiplexers are required to switch in between channels. For example, the KHU Mark2 [13] system with frequency range of 10 Hz to 500 kHz, and the Dartmouth system (published in 2008) [14] expanded the working frequency to more than 2 MHz. The significant advantages of the parallel structure are faster data acquisition speed, flexible stimulation strategies, and reduced effects of parasitic capacitances at higher frequencies. The Dartmouth system even eliminated as much as possible analog circuits in the analog frontend unit to further reduce parasitic capacitances and improve impedance measurement performance at higher frequencies.

In real medical application, for safety purpose, the excitation currents are generally less than half mA. Accurate calibration of excitation currents on all front end channels may be a big challenge and timing consuming. As a compromise, semi-parallel EIT systems are developed with one pair of stimulators and parallel voltmeters. For example, the Leeds System (published in 2005) [15] developed with electronic components for industrial applications, the KHU Mark1 (published in 2007) [16] and the most recent Dartmouth system (published in 2015) [17] implemented with commercialized expensive National Instrumentation (NI, USA) function modules. The Dartmouth system (2015) is great for research but a bit expensive for commercialization of the EIT system. The four NI modules quoted more than 25k US dollar on NI website (www.ni.comwww.ni.com). All the three systems have their circuit modules packed in a chassis and so, long electrode cables are necessary for signal transmission. The long cables introduce parasitic capacitances and result in degradation of impedance measurement performance at higher frequencies.

Started from the motivation to design a medical EIT system [18,19] that has stable performances in the spectrum range from 1 kHz to 1 MHz, with deep consideration of patient safety and ease of hardware upgrades and scalability, a modular semi-parallel EIT Data Acquisition System (DAS), SJTU Mk-1, have been recently developed and presented in this paper. The system structure, the control module, the frontend module, and the compound electrode array are introduced. System performances are calibrated in terms of transfer impedance with resistor rings and water phantom. Excitation current amplitude is set to less than half mA, the same as how it will be used in medical application. The calibration results are presented.

2. Design of the EIT data aqcuisition system

2.1. Architecture design

The architecture of the SJTU Mk-1 EIT DAS is described in Fig. 1. It features modular design and minimized lengths of electrode cables. The system has four key function blocks: a control module, a power supply module, sixteen frontend modules, and a ribbon cable with seventeen connecting slots numbered from 1 to 17. Slot 17 is the only one that is on the outer side of the ribbon cable, connecting with the control module. The rest of the 16 slots are installed in the inner side of the ribbon cable and equal spaced for easier time compensation of signal transmission. Time compensation is achieved by careful PCB layouts on control module and frontend modules by making signal trances from different slots the same length. This is very important for accurate phase measurement at higher frequencies.

Each frontend module is closely connected with one compound electrode [20], via a pair of short flexible cables for current and voltage signal transmissions. The frontend modules are then plugged into ribbon cable slots 1–16 for power supply, signal transmission, and communication with controller module. Signals are interleaved and shielded by ground lines in the ribbon cable to reduce crosstalk noises. A significant difference of the SJTU Mk-1 EIT DAS system from others is that, instead of all circuits assembled in a compact chassis, all the frontend modules are placed closely around the target to minimize parasitic capacitances of electrode cables.

The compound electrode and electrode array is shown in Fig. 2. Compound electrodes allow excitation and measurement at the same location and hence independent measurement number can

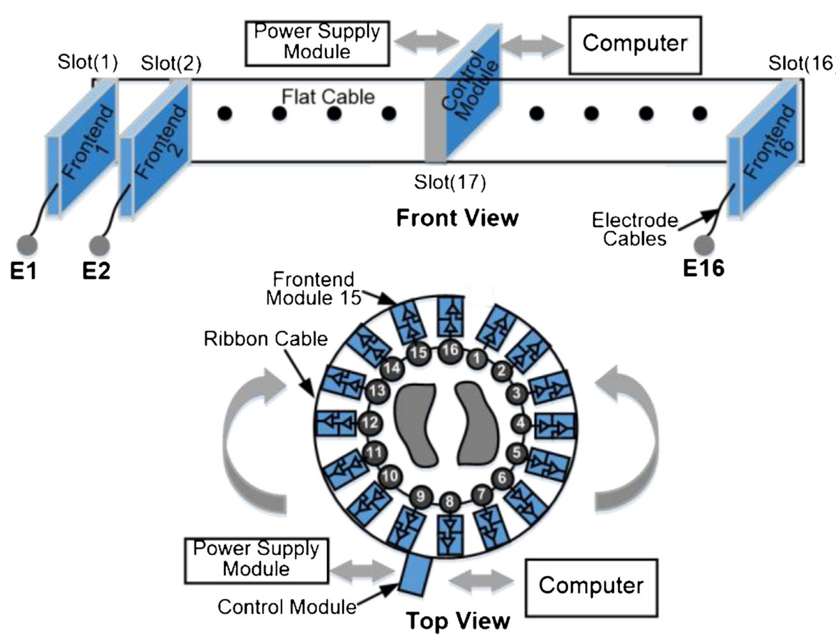

Fig. 1. Architecture of the modular design of SJTU Mk-1 EIT DAS.