Abstract— Electrical Impedance Tomography (EIT) is a functional real-time imaging technique, mainly used in medical applications. EIT is based on impedance measurements of an object under test and the reconstruction of its spatial impedance distribution. EIT is painless, low-cost, works without ionic radiation and has no known hazards.

Irreversible Electroporation (IRE) is an ablation technique, based on the permanent permeability change of the cell plasma membrane due to an applied electric field.

This work presents a novel EIT system designed for measurement, visualization and feedback of IRE. The developed system employs two electrode plates surrounding the target tissue for data acquisition. It enables impedance spectroscopic measurements in real-time, is modular arranged and based on a Field Programmable Gate Array (FPGA) System on Chip (SoC) that is connected to host PC. The embedded system is in charge for data acquisition, preprocessing and transmission, whereby the host PC provides further filtering, data conditioning and the subsequent image reconstruction and display.

I. INTRODUCTION

Electrical Impedance Tomography (EIT) is a medical imaging technique, based on measurement and reconstruction of spatial impedance distributions within an object under test. For the measurements small known alternating currents (AC) are injected via electrodes into the object under test. The resulting boundary voltages are subsequently measured. Based on these measured voltages and the known currents an image of the spatial impedance distribution can be reconstructed. EIT has no known hazards and allows real-time measurements without ionic radiation [1] [6] [8]. Beside the usage in medical settings EIT is also used in industrial applications e.g. for pipe and tank monitoring [13-14] and in large scale applications in geophysics, for example in soil composition [12] and geological layer analysis [11].

Electroporation is the significant increase of the electrical impedance of cell plasma membranes, caused by external applied high voltage pulses. Depending on the magnitude and duration of the applied voltage pulse the effect of electroporation can be a temporarily called reversible electroporation or permanently called irreversible electroporation (IRE) [1] [5].

Discovered in the late 1960s electroporation is now used for gene therapy [2] and drug therapy in the reversible mode [3] and for ablation of tissue in the irreversible mode [4]. For IRE electric fields up to 1000 V/cm are used, which are causing a subsequent cell death [7]. Currently amplitude and duration of the IRE are solely based on the experience of the surgeon, caused by a lag of suitable real-time feedback systems [7].

This work presents a novel EIT system which is designed to provide functional real-time impedance spectroscopic images of the tissue under electroporation to enable online feedback to the surgeon.

The presented system is based on a Field Programmable Gate Array (FPGA) System on Chip (SoC). FPGAs are powerful electronic logic devices, which can be individual programmed by use of a Hardware Description Language (HDL). In difference to a microcontroller, a FPGA can process tasks in parallel and allow therefore a much more powerful task handling.

II. SYSTEM ARCHITECTURE

To obtain a good image resolution and a large image area, 64 electrodes will be used. For that purpose two 32 electrode EIT systems will be linked together. Figure 1 shows the principle build-up.
troporator. Figure 2 shows a block diagram of the complete system.

![Fig 2. Principle system architecture of developed EIT System](image)

The electroporator consists of a high voltage pulse generator, cables and two small stainless steel needles. The needles have a diameter of about 400 μm and will be stabbed directly into the tissue during the operation. The electrode plates of the developed EIT system will be placed around the tissue under surgery. To protect the system against high voltage pulses (electronic) relays in series with the plates allow a disconnection of the electrode plates in case of the detection of an active electroporation. For that purpose the cables of the electroporator are monitored permanently via voltage probes. The actual embedded EIT system consists mainly of a control unit, a voltmeter and a current source as well as a multiplexer to connect the blocks to the different electrodes. The embedded System is connected via USB to a host PC for data transmission and control. For patient safety issues an appropriate galvanic isolation is also established in the USB connection. The host PC implements further signal conditioning and filtering, as well as the actual image reconstruction.

### III. Electrode Plates

The electrode array used for the contact to the object under test is shown in Figure 3. Each of the two plates is equipped with 32 electrodes, which are gold coated to prevent oxidation and to maintain low contact impedances.

Low contact impedances are important for accurate measurements [8], therefore a further contact impedance improvement is achieved by electrochemical deposition of platinum [9]. In order to avoid measurement errors due to contact impedances normally a four electrode setup is used. While one pair of electrodes is used for the current injection, the other electrode pairs are used for voltage measurements. For the given number of electrodes this results in 208 independent measurements.

In contrary to other EIT applications, in electroporation the electrodes can be placed directly on the tissue, omitting the high contact impedance of the human skin. Therefore it can be assumed that the use of the simpler two-electrode method is trouble-free, as long as the electrodes are used in an appropriate frequency range and operated with a low current density.

To allow measurements at different scales, two different sets of electrode plates have been manufactured – one set with 5 mm spacing and one set with 10 mm spacing. Figure 4 shows a photograph of a prototyped electrode plate.

![Fig 4. Manufactured electrode plate PCBs with connectors (right) and electrodes (left). The electrodes are aligned on a 5 mm grid.](image)

### IV. Hardware

The embedded system is based on a SoC FPGA architecture. The FPGA (LFXP2 from Lattice Semiconductor) governs data acquisition, data pre-processing and data transmission in real-time. It is easy programmable and reconfigurable to adapt to varying conditions as common in research settings. Figure 5 shows a detailed block diagram of the EIT system.
Fig 5. Block diagram of the developed EIT system. The object under electroporation is located between two electrode plates. The data acquisition and stimulation is enabled by two ADC in combination with two PGA and a DAC. An embedded SoC running on an FPGA governs the measurement process and commands a disconnection in case of an active electroporation. Image reconstruction and display are subsequently done on a host PC, which is connected via a high speed USB link.

The generation of the required AC is realized with a Digital to Analog Converter (DAC, LTC1668 from Linear Technology) with 16 bit resolution and up to 50 MSPS in combination with an interpolation filter and a voltage to current source. The DAC is able to generate arbitrary waveforms by usage of Direct Digital Synthesis (DDS) techniques. The excitation frequency is adjustable in a range from 10 kHz to 250 kHz. Beside conventional sinusoidal signals also linear chirps or any other signal overlay can be generated in order to minimizing the required data acquisition time for broadband impedance measurements [9]. To maintain an optimal current density at the electrodes a Programmable Gain Amplifier (PGA, AD8250 from Analog Devices) is used. The current can be adjusted in four steps in a range of 500 μA to 5 mA according to the IEC 60601-1.

As shown in Figure 5 a multiplexer is used to connect the current source to the electrode plates. Because of the phase shift and attenuation of the multiplexer the output current is falsified. To increase the measurement accuracy an additional low side current shunt is employed to measure the actual excitation current.

The voltage measurements are realized using a two channel 40 MSPS (mega samples per second) Analog to Digital Converter (ADC, LTC2297 from Linear Technology) with a resolution of 14 bit in combination with band pass filters and PGAs. The PGAs have four different amplification factors (1, 2, 5 and 10) to allow an optimal match to the ADC input voltage range and therefore to an optimal Signal to Noise Ratio (SNR). To maintain a high SNR band pass filters will be used to attenuate noise and interferences outside the interesting frequency range. Because of the known limitations of analog filters, inside the FPGA an additional Finite Impulse Response (FIR) filter is implemented to enable high filter orders. Contingent by the high sample frequency of the ADCs multi-rate signal processing in terms of oversampling and decimation is possible. This multi-rate approach enables an elegant signal processing and reduction of the measurement data.

The actual signal demodulation is done digitally with a Fast Fourier Transformation (FFT) based approach, which allows amplitude and phase measurements over a broad frequency range.

Figure 6 shows a photograph of the manufactured prototype of embedded EIT system PCB.

Fig 6. Assembled prototype of the developed embedded EIT system PCB.

The data transmission between PC and embedded system is realized with a powerful USB 2.0 interface in high speed mode, capable of data rates up to 40 MByte/s. The claimed galvanic isolation is achieved with an optically coupled USB hub (USB 2 Isolator STD 2224 from Baaske Medical).

The implemented firmware is designed modularly, while data acquisition and preprocessing are implemented directly on the FPGA. The actual image reconstruction is done on the host PC with Mathworks MATLAB in connection with EIDORS [10]. This modular build-up allows maximum flexibility in terms of exchangeability and extensibility to provide ideal conditions for research purposes. Figure 7 show an overview of the FPGA Firmware.

Fig 7. Overview of the implemented FPGA firmware and its module separation. The firmware has a clear structure. All modules are controlled and interfaced by the Control Logic block, which contains the system state machine.

V. CONCLUSION AND FUTURE WORK

A prototype of a multi-frequency EIT system for the usage as electroporation feedback system is designed, developed and manufactured. The prototype is able to gener-
ate arbitrary waveforms and measures transfer impedances in a frequency range of 10 kHz to 250 kHz. The system promises high data quality, furthermore it can be expected that data collection will contribute to a better understanding of the electroporation and will provide a real-time feedback for electroporation.

Before first in vivo tests can be done the system has to be fully operational in term of software development and further hardware tests. Afterwards first phantom tests and ex vivo tests have to be carried out.

By now as a future improvement a new electrode setup is planned to allow real 3d measurements of object under test. For that purpose up to four embedded EIT systems will be interconnected to increase the amount of electrodes.

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REFERENCES


