Portable sounding pulse generator for electrical impedance tomography systems

E S Korolyuk* and K S Brazovskii1
1Tomsk Polytechnic University, Tomsk, Russia
E-mail: esk13@tpu.ru

Abstract. Cryosurgery is a surgical method of biological tissue removal at extremely low temperatures. One of the main issues of cryosurgery is low accuracy in determining the boundaries and depth of frozen tissue. This paper presents the results of the development of a sounding pulse generator for evaluation of the electrical characteristics of biological objects during cryodestruction. The developed sounding pulse generator is a part of the experimental system for the development of a tomograph, using the principle of electric impedance tomography. This paper presents an experimental prototype of the sounding pulse generator applied to study the impedance properties of biological tissue in a wide temperature range from minus 196 °C to plus 50 °C. The application field for the developed generator: medical systems for visualization of boundaries and depth of biological tissue freezing during cryosurgical operations.

1. Introduction
Cryotherapy has become firmly established among various medical fields. Methods of destruction of pathological tissues by means of cold are used to remove a variety of benign and malignant formations. Painlessness, accessibility, simplicity of a local cold exposure distinguishes this method from other types of surgical treatment [1, 2].

At present, the project team is working on the creation of an experimental unit, which allows to measure the depth and boundary of tissue freezing by means of electric impedance tomography [3, 4]. The main element of the experimental unit is a visualization system that operates on the principle of electric impedance tomography [5-7]. The visualization system consists of two components - a transmitter, which is a sounding electrical impulses generator and a receiver - an analog-to-digital converter, which determines the potential difference between the electrodes in the investigated object. This paper presents the design and experimental research with the use of biological objects by means of the developed prototype of the sounding pulse generator, which is part of the experimental unit.

A sounding pulse generator is essential for monitoring thermophysical processes and visualizing the freezing process. The device must be capable of delivering electrical pulses of safe level through the test samples, the temperature of test samples varying from minus 70 °C and below to plus 30 °C.

2. Design and manufacturing of the sounding pulse generator
The first step in the sounding pulses generator construction was the design of a structural scheme taking into accounts the technical requirements: the output frequency should be between 10 kHz and 1 MHz, the maximum amplitude of the output current should be in the safe range of 20 mA.
Due Considering the technical requirements, the structure scheme shown in Figure 1 has been proposed [3].

![Figure 1. Structure scheme of the sounding pulse generator module.](image)

The designed module consists of the following components: control system, reference voltage source, digital-to-analog converter and matching transformer.

**Control system.** The Stm32f1 microcontroller (STMicroelectronics as a manufacturer) is offered as the main component of the digital-to-analog converter chip control system since it has a number of advantages: simplicity of development, low cost, low power supply voltage, and the necessary speed to perform tasks for generating sounding signals.

**Power Source.** To increase the quality of the output signal, it is necessary to minimize electromagnetic interference on the PCB as much as possible. One of the main sources of interference is interference on the PCB via the power supply circuitry. In order to minimize interference on the power supply circuit, it has been decided to use a linear stabilizer AP1117 with an output voltage of 3.3 Volts [8]. The board will be powered via a micro-USB connector with an external power supply.

**Digital-to-analog converter.** A digital-to-analog converter (DAC) is required to generate output sounding pulses to the studied object. For this component of the device there are high requirements to the quality of the reproduced signal. Also, the DAC must be fast enough to generate high-frequency signals, have a high bit rate and low level of natural interference. The AD9764 chip (Analog Devices as a manufacturer) was chosen as the DAC. The maximum frequency of this converter is up to 125 MV/s (mega samples per second), the bit rate is 14 bits. There is an internal source of reference voltage inside the chip with the possibility of external source connection [9].

**The Reference voltage source.** Reference voltage sources are used to form a precision low-noise voltage of known magnitude with minimum temperature and time drifts. For qualitative conversion of digital data stored in the microcontroller memory into a high-quality analog signal, DAC requires a reference voltage source. ADR3412 chip with the following characteristics was chosen as an RVS: output voltage - 1.2 Volts, accuracy 0.1%, maximum temperature coefficient 8 ppm/°C [10].

**Matching transformer.** A matching transformer is required to match the load between the DAC chip output and the studied object. A broadband transformer from the Coilcraft with frequency characteristics from 10 kHz to 100 MHz was chosen as a matching transformer.

The next step was the design of the circuit diagram and circuit board layout of the device (figure 2). The KiCad software version 5.1.4 was used as the design interface [11].

![Figure 2. Digital prototype of the front and back side of the PCB, where: 1 - step-down converters for powering board components, 2 - programming connector, 3 - microcontroller, 4 - reset button, 5 - digital-analog converter, 6 - signal transformer, 7 - slots for SMA connectors, 8 - slot for micro-USB connector (necessary for power connection).](image)
After manufacturing the digital prototype, the developed board was transferred to JLCPCB for production. The finished printed circuit board is shown in Figure 3.

![Figure 3. The front (left) and back (right) side of the manufactured circuit board.](image)

The next step after checking the manufactured PCBs was to install the necessary chips and to solder them. The final step was putting the program code into the microcontroller. The finished printed-circuit board after installation and soldering of all necessary elements is shown in Figure 4.

![Figure 4. The front side of the manufactured circuit board with soldered components.](image)

### 3. Software

The program operation is shown in Figure 5, and works according to the following principle:

- When the unit is powered up, the microcontroller peripherals are initialized and configured. The following modules are configured: clocking module, input/output interface (GPIO), timers, direct memory access module (DMA).
- After initialization of the module, the program enters an infinite main circuit. Within the circuit, the operation of the unit is indicated.

Data transfer to the DAC chip is performed with the DMA module without the participation of the microcontroller core. The work of the DMA module sub-program is shown in Figure 5 (right).

![Figure 5. The front side of the manufactured circuit board with soldered components.](image)
4. Temperature measurement of the investigated objects

The In order to accurately determine the temperature of the investigated objects during the experimental studies, we had to develop a device allowing to measure the temperature with the necessary accuracy in the range from minus 70 °C to plus 30 °C.

It was suggested to use MAX31855 chip and K-type thermocouple as a temperature meter. This chip can work with different types of thermocouples and determine the temperature from minus 270 °C to plus 1800 °C with a resolution of 0.25 °C (for K-type thermocouples the temperature measurement is in the range from minus 200 °C to plus 700 °C with an accuracy of 2 °C at the extreme limits of the range) [12].

For the rapid manufacturing of the module and saving time, a ready-made temperature measurement module with the MAX31855 chip, shown in Figure 6, was used. An Arduino Nano ready-made module with an Atmega328p microcontroller was used as the control system. The control system is necessary for the primary setting of the module, reading the measured temperature, conversion of primary data received from the chip MAX31855 in a user-friendly format, transfer of measured temperature to the control system of the experimental unit.

![Figure 6. The front side of the module, where: 1 - temperature measurement module; 2 - module control system.](image1)

The data is transmitted via USB protocol by means of virtual COM port emulation. The received data of the measured temperature are sent to the control system of the experimental unit and are shown in Figure 7.

![Figure 7. The data obtained from the temperature measuring module using the Terminal 1.9b software, where: 1 - measured temperature in degrees Celsius.](image2)
Before the start of experimental research, the developed module was tested in various temperature ranges. To check the accuracy of temperature measurement, a HoldPeak HP890CN multimeter with a k-type thermocouple connected was used as a reference thermometer. The device readings were compared with temperature ranges from minus 196°C to plus 20°C. The results obtained during the experiment are shown in Figure 8.

![Figure 8. Comparison of obtained results.](image)

The maximum data dispersion is observed in the temperature range from minus 190°C to minus 140°C and is not more than 4°C. As the temperature rises above minus 140°C, the dispersion starts to decrease. From minus 100°C to plus 20°C, the dispersion does not exceed 1°C.

According to the data obtained, it can be concluded that the developed temperature measurement module meets the necessary requirements and can be used in the designed experimental unit.

5. Design and manufacturing of a housing for a sounding pulse generator

The last stage in the design of the sounding pulse generator was the construction of the case (figure 9), which meets the following criteria:

- The case must protect the generator board from external environmental influences.
- The case design must be ergonomic and comply with the basic principles of industrial design.
- The lower edge of the case, which covers the textolite board, should be "embedded" in the upper cover, with a minimum gap, to provide additional protection for the generator from external influences.

![Figure 9. The case designed in Autodesk Inventor 2019 environment (left) where: 1 - top case cover; 2 - textolite board; 3 - bottom case cover. The assembled device (right).](image)
The case was constructed with the help of 3D printing technology; the textolite board was fixed in the slots with screws and self-tapping screws. All necessary connection wires are plugged into the appropriate connectors.

6. Results and Discussion
To determine the dependence of electrical parameters values on the temperature and degree of biological tissue destruction, a number of experiments with different test samples were carried out: a 2000 ohm and 20 kohm resistor, an apple, beef muscle tissue. The test sample was placed on a radiator used for cooling and heating. For better contact a cryosensor was pressed onto the test sample, as shown in Figure 10 (left).

A sounding pulse generator module and an analog-to-digital converter are connected to the upper part of the cryosensor using SMA connectors and a coaxial cable. The temperature measurement was carried out using a thermocouple connected to the temperature measurement module. After all modules had been connected, the investigated sample was placed in a cooling system as shown in figure 10 (right). Cooling was carried out by injecting small amounts of liquid nitrogen into the cooled unit. By changing the amount of liquid nitrogen supplied to the thermal insulation chamber, we controlled the cooling rate of the metal radiator and the test sample.

Figure 10. Connecting the cryosensor to the tested sample (left) and carrying out the experiment (right).

7. Measurement of the impedance of known resistance values
For testing the sounding pulse generator and the experimental prototype of the unit for visualization of the borders and the depth of freezing of biological tissues, we used precision smd resistors with the already known resistance of 2 kOhm and 20 kOhm and permissible deviation no more than 0.1%. [13, 14]. Resistor impedance was measured in the frequency range from 5 kHz to 500 kHz. The measurement results are shown in Figure 11. The error of impedance measurement is rather low and allows making measurements with the given accuracy.

Figure 11. Measuring impedance spectrum of precision smd resistors with 2kOhm and 20kOhm ratings. Y axis - impedance in Ohm on logarithmic scale, X axis - frequency in Hertz on logarithmic scale.
8. The impedance measurement of a green apple

The experiments were devoted to the study of green apple impedance in the frequency range from 5 kHz to 500 kHz. A piece of a green apple with removed peels and seeds was used as a test sample. The initial temperature of the test sample was plus 20 °C and the temperature was cooled to minus 50 °C. The results of the experiments are shown in Figures 12 and 13.

At the beginning of the experiment, the impedance of the tested object is constant and decreases exponentially with increasing frequency. While cooling the investigated sample, the impedance smoothly increases over the whole frequency range, as shown in Figure 13. The gradual increase in impedance continues until the formation of ice crystals in the test sample. At minus 1 °C, the last spectrum of apple tissue was measured before the ice formed inside the cells (ice crystals formation). At minus 2.9 °C, the ice formation is faster and the impedance increases rapidly over the entire frequency range. At minus 6 °C, the sample is completely frozen and the rapid impedance increase is stopped. Compared to the liquid phase (before the formation of ice inside the cells), the impedance has increased by about 100 times (2 orders of magnitude). With further cooling of the test sample, the impedance continues to increase, but not so rapidly. After cooling the sample of a green apple to minus 50 °C, the impedance increased approximately 2-4 times in the frequency range from 5 kHz to 100 kHz compared to minus 6 °C. In the frequency range from 100 kHz to 500 kHz the impedance increased slightly compared to minus 6 °C.

Figure 12. The bioimpedance spectrum of a green apple. Y axis - impedance in Ohm on logarithmic scale, X axis - frequency in Hertz on logarithmic scale.

Figure 13. The bioimpedance spectrum of a green apple. Y axis - impedance in Ohm on logarithmic scale, X axis - frequency in Hertz on logarithmic scale.
9. The impedance measurement of beef muscle tissue
Subsequent experiments were devoted to the study of muscle tissue impedance in the frequency range from 5 kHz to 500 kHz. The muscle tissue of beef without any visible fat or veins was chosen as a test sample. The initial temperature of the test sample was 22 °C and the cooling was carried out to minus 52 °C. Bioimpedance spectrum of beef muscle tissue obtained as a result of the experiments shown in Figures 14 and 15.

Like in experimental studies with a green apple, muscle tissue impedance is constant and increases over the whole range with gradual cooling of the test sample. In the frequency range from 5 kHz to 500 kHz the impedance is practically unchanged. As the temperature drops and ice crystals begin to form in muscle tissue, the impedance increases sharply over the whole frequency range. Having cooled muscle tissue to a temperature of minus 52 °C, the impedance increased by about 1000 times (by 3 orders of magnitude) compared to the measured spectrum where ice formation had not yet begun (the temperature was plus 1.35 °C). When the temperature of the investigated object is equal to plus 2.2 °C and below, there is an exponential growth of impedance in the frequency range starting from approximately 130 kHz.

![Figure 14. The bioimpedance spectrum of a beef muscle tissue. Y axis - impedance in Ohm on logarithmic scale, X axis - frequency in Hertz on logarithmic scale.](image)

![Figure 15. The bioimpedance spectrum of a beef muscle tissue. Y axis - impedance in Ohm on logarithmic scale, X axis - frequency in Hertz on logarithmic scale.](image)

10. Related work
In this research, an early version of an experimental facility for visualizing the boundaries and depth of freezing of biological objects using the principle of electric impedance tomography was
demonstrated. The system we have developed allows us to make measurements with the required accuracy, which is necessary to determine the degree of freezing of the studied object. In the future we hope to significantly upgrade the developed prototype - to increase the number of channels (one channel is currently used); to expand the frequency range up to the megahertz frequency units; to develop software that allows to analyze and visualize the degree, boundaries and depth of freezing of the investigated object; to develop our own analog-to-digital converter module.

11. Conclusions
This paper demonstrates the design of a sounding pulse generator for a compact experimental tomographic working on the principle of electrical impedance tomography. With the help of the designed prototype we conducted experimental studies on bioimpedance properties of various biological samples such as green apple plant tissue and beef muscle tissue. During cooling and further freezing of the investigated samples we have observed a sharp increase in impedance by 100 - 1000 times.

During the experimental studies, we have studied the spectral dependencies and the bioimpedance properties of such biological objects as green apple tissue and beef muscle tissue at temperatures ranging from plus 20 °C to minus 52 °C. In general, changes in the spectra of both samples are similar and can be divided into several stages:

1. The initial stage. The test sample has room temperature. At this stage, the bioimpedance spectral characteristic is constant and has a minimum value over the whole investigated frequency range;
2. Cooling. During cooling, the bioimpedance spectrum starts to increase and grows smoothly as the temperature drops till the ice crystals formation;
3. The freezing process begins. At this stage ice crystals begin to form on the surface and inside the investigated samples. Impedance starts to increase dramatically and change its characteristic. Depending on the type of investigated object there can be an increase or decrease of impedance values in a certain frequency range, relative to the rest of the spectrum;
4. Freezing. The impedance spectral characteristic continues to increase sharply until all the fluid inside the tissue freezes. Depending on the type and structure of the tissue the temperature at which the final freezing occurs is different. The differences in temperature are due to the different structure of different types of tissue, the differences between plant and animal tissue. For plant tissue (green apple as a sample) the final freezing temperature, after which the impedance spectrum increased slightly varies between minus 1.3 °C and minus 2.9 °C. For animal tissue (beef muscle), the final freezing temperature was much lower and is in the approximate range of minus 31 °C to minus 52 °C.
5. Complete freezing. At this stage, the test sample is completely frozen and the impedance changes slightly with a further decrease in temperature.

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