Bioelectrical impedance analysis of bovine milk fat

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Abstract. Three samples of 250ml at home temperature of 20ºC were obtained from whole, low fat and fat free bovine UHT milk. They were analysed by measuring both impedance spectra and dc conductivity in order to establish the relationship between samples related to fat content. An impedance measuring system was developed, which is based on digital oscilloscope, a current source and a FPGA. Data was measured by the oscilloscope in the frequency 1 kHz to 100 kHz. It was showed that there is approximately 7.9% difference in the conductivity between whole and low fat milk whereas 15.9% between low fat and free fat one. The change of fatness in the milk can be significantly sensed by both impedance spectra measurements and dc conductivity. This result might be useful for detecting fat content of milk in a very simple way and also may help the development of sensors for measuring milk quality, as for example the detection of mastitis.

1. Introduction
Over a decade the Bioelectrical Impedance Analysis (BIA) is being investigated as a potential technique for tissue characterization [1,2]. BIA technique has also been widely used to evaluate body composition and the quality of food, water and milk [3,4,5]. This technology is relatively simple, quick and noninvasive way for obtaining the impedance spectrum of the material under study. The impedance can be related to an equivalent electrical model of the material in order to fit to the measured data [6].

In order to obtain the most biological information, multi-frequency excitation signal should be required. It can be done by using multiple Direct Digital Synthesizer (DDS) in order to produce discrete frequencies in the time domain, and then sine waves are obtained by filtering the high-frequency harmonics [7]. Digital Signal Processing (DSP) integrated circuits (IC) are also widely used for this purpose, but they suffer from speed, power consumption and limiting number of storage points [8]. Furthermore, the number of bits available in its internal D/A converter is limited and so the precision of the signal generator is reduced. Multi-frequency systems use multiple DDS but the synchronization is also difficult [8]. Field-Programmable Gate Array (FPGA) has been proposed as a hardware technology for DSP systems. It can develop the most suitable circuit architectures in terms of computing, memory storage and power consumption in a similar way as DSP [8]. The FPGA Spartan 3 from Xilinx Inc. provides a DDS that can be used to generate multi-frequency sine waves. Though, bioelectrical impedance analyser can be easily developed by using a FPGA circuit.

Bovine milk is one of the most consumed food in the entire world. The fat present in the milk is a parameter that has great importance for dairy industry. For many reasons, consumers ask for information about the food they are purchasing, especially for people who have clinical recommendations regarding the consumption of saturated fat. Electrical measurement is a simple tool for material characterization and it is been of most interest for checking quality and fat content [9,10].
The main objective of this work is to investigate the conductivity spectra of three types of bovine milk by measuring the electrical impedance spectra.

2. Methodology

Three samples of 250ml at about 20°C were obtained from free fat (skimmed), low-fat (semi-skimmed) and whole UHT milk. Analyses were performed by measuring both impedance spectra and conductivity. The system setup is shown in figure 1.

![Figure 1](a) Block diagram of the implemented BIA system. (b) Transversal view of the impedance probe tip, where A,B are injecting electrodes and C,D are receiving electrodes, where the electrode diameter is 1 mm.

2.1 Signal Generator

The sine wave generator is based on FPGA Spartan 3 from Xilinx (model XC3S200 Starter kit board), which contains a DDS module with a phase generator and a sine/cosine lookup table [10]. The output frequency is controlled by a Phase Increment (PINC_IN). The equation (1) shows the relationship between the output frequency \( F_{out} \) and the PINC_IN.

\[
F_{out} = \frac{F_{clk} \times PINC_{IN}}{2^L}
\]

where \( F_{clk} \) is the system clock frequency and \( L \) represents the number of bits in the phase accumulator.

The data was converted to digital by a DAC (Digital to Analog Converter) of 8 bits at a sampling rate of 667 kHz. In practice, 10 discrete frequencies were generated in the frequency range from 1 kHz to 100 kHz.

2.2 Current Source

The voltage signal is converted into a current by a modified Howland bipolar current source [11], which converts an input voltage of 2 Vpp (peak-to-peak) to an output current of 1mApp over the frequency range. The current is injected by two electrodes of the probe, which contains 8 gold electrodes (see figure 1b).

2.3 Measuring System

The signal acquisition was done by using the MSO 4034 oscilloscope from Tektronics [12], which has a bandwidth of 350 MHz and a sample ratio of 2.5GS/s. The differential voltage was measured cross other two electrodes of the probe by using the oscilloscope. The oscilloscope was connected to a PC based on the HTTP communication protocol. Data was recovered by using a Matlab interface and then both impedance and conductivity \( \sigma (=1/\rho) \) spectra were calculated (see equation 2). In order to calculate the impedance at dc frequency, a conductivity meter (model CD4303) from Digital Instruments was used to measure the dc conductivity of the samples (see equation 2).
\[ \frac{Z_{calc}}{2\pi} = \frac{\rho}{\gamma} \]  

(2)

where \( \rho \) is the medium resistivity and \( \gamma \) is the probe factor given by equation 3.

\[ \gamma = \left( \frac{1}{R_{AC}} - \frac{1}{R_{AD}} + \frac{1}{R_{BD}} - \frac{1}{R_{BC}} \right) \]  

(3)

where the electrode distances AC, AD, BD and BC are given in figure 1.

The bovine milk samples are UHT type from milk manufacturer. The contents of sodium, calcium, proteins and carbohydrates are similar for the three types of milk used, as shown in table 1.

### Table I. Milk contents for a volume of 200ml, according to the manufacturer.

| Milk type  | Carbohydrate (g) | Protein (g) | Fat (g) | Calcium (mg) | Sodium (mg) |
|------------|------------------|-------------|---------|---------------|-------------|
| Whole      | 9                | 6           | 6       | 230           | 138         |
| Low-fat    | 9                | 6           | 2       | 230           | 138         |
| Fat free   | 9                | 6           | 0       | 230           | 138         |

#### 3. Results

The impedance was calculated by measuring both injecting current and resulting voltage. The measurements were collected 10 times for each type of milk at each discrete frequency. The time estimated for taking each measurement in specified frequency was 8.6 seconds. Table 2 shows the mean impedance modulus for each type of milk and its respective conductivity obtained from CD4303.

### Table II. Measured milk conductivity from CD4303 at 20°C.

| Milk type  | Conductivity (mS/cm) |
|------------|-----------------------|
| Whole      | 3.62                  |
| Low-fat    | 3.91                  |
| Fat free   | 4.63                  |

Figure 3 shows a variation of approximately \( \pm 1.3 \% \) in the milk impedance modulus below 50 kHz whereas \( \pm 4 \% \) at 100 kHz. The impedance modulus increases as increasing fat content.

Table 3 shows the mean values of the measured impedance \( (Z_{meas}) \) and the calculated impedance \( (Z_{calc}) \) from equation 2 by using the data from table 2.

### Table III. Both measured and calculated milk impedance at 20°C

| Milk type  | Fat (%) | Mean \( Z_{meas} \) (Ω) (figure 3) | Mean \( Z_{calc} \) (Ω) (equation 2) |
|------------|---------|------------------------------------|-------------------------------------|
| Whole      | 3       | 219.56                             | 168.38                              |
| Low-fat    | 2       | 203.57                             | 155.89                              |
| Fat free   | 0       | 170.08                             | 131.65                              |
Figure 3. Impedance modulus of the milk in the frequency range from 1 kHz and 100 kHz.

Figure 4 shows the relationship between the calculated (continuous lines) and measured (bullet lines) conductivity over the frequency range of 1 kHz to 100 kHz. It can be seen that the conductivity data are different and the maximum error is approximately 23.3%. This might be explained by the fact that the conductivity meter probe has a different geometry (ring electrodes) and then the probe factor is different.

Figure 4. Bovine milk conductivity spectra from 1 to 100 kHz.

4. Discussions and Conclusions
The electrical conductivity spectra of bovine milk by using impedance measurements over the frequency range from 1 to 100 kHz were performed. It was showed that there was a conductivity difference of approximately 7.9% between whole and low-fat milk whereas 15.9% between low-fat and free fat one.

Although the concentration of calcium is similar for each type of milk, it was found that there is a change in the impedance modulus as fat concentration changes. There might be explained by the fact that there are other types of ions in the milk which may contribute for the current flow.
The maximum difference between calculated conductivity from impedance spectra and measured conductivity from CD4303 was approximately 23.3 %, which can be corrected by changing the probe factor. It must be emphasized that the conductivity meter uses the two electrode technique whereas the impedance spectra used the four electrode method.

It can be concluded that the change in the fat content of milk can be significantly sensed by both impedance and conductivity spectra measurements. This results might be useful for detecting milk fatness in a very simple way and also it might help the development of sensors for measuring milk quality, as for example mastitis.

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