Initial Results on Primary Field Cancellation of Magnetic Induction Spectroscopy Technique for Fetal Acidosis Detection using COMSOL Multiphysics

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Abstract. Monitoring of fetal condition during labor could save hundred lives in a single year. During labor, fetus is at critical condition as acidosis may occur suddenly without any early symptoms. Invasive method such as Fetal Blood Sampling (FBS) has been used to detect the decline in pH level of fetus. However, fetal loss rate after FBS may range from 1.4% up to 25%. In this paper, magnetic field induction spectroscopy was implemented to determine fetal acidosis by using primary magnetic field cancellation technique. Magnetic Induction Spectroscopy (MIS) probe was design where transmitter coil (TX) is perpendicular to receiver coil (RX). The result shows that the secondary magnetic field produced have been successfully measured without any interruption from primary magnetic field. By using transmitter input 1A, it shows that voltage is inversely proportional to the blood pH due to the conductivity properties of blood.

1. Introduction
Fetal monitoring is a crucial procedure during labor which indicates fetal distress and acidosis due to oxygen deficiency. Over the centuries, several techniques have been used to assess the fetal health and decide the needs of emergency caeserian section. Fetal blood sampling (FBS) and cardiotocography (CTG) are among the leading techniques used today which are both invasive and non-invasive method respectively. In the past few years, a new technique using Magnetic Induction Spectroscopy (MIS) has been reveal could obtain the bioimpedance spectroscopy measurement of human tissue [1] for various application such as to distinguish an instantaneous pH value [2],[3]. Thus, intensive study has been done to understand the model by simulation and prototype. This paper presents an application of
perpendicular MIS coil specifically for determination of fetal acidosis according to scalp pH value and its associated induced voltage produced by the scalp tissue.

MIS technique is very convenient since it is simple, non-invasive, free from electrode, could eliminate the electrical hazards and inexpensive [1],[4]. The working principle is based on Maxwell Equations, Faraday’s Law and Lenz Law. MIS design consists of only two coils (TX and RX) connected to microcontroller and display. In MIS system, a small current value and frequency range within beta dispersion region [5] is supplied to transmitter coil creates magnetic field penetrates into the fetal scalp (Figure 1). A slight acidic nature of blood contains hydrogen ions electrolyte which conduct electricity, thus induces eddy current in the blood and creates its own field called, secondary magnetic field and detect by receiver coil [6]. The reading is dependent of sample electrical properties (conductivity, permittivity and permeability) and input frequency [7].

![Figure 1. Eddy current production in conductive material [8]](image1)

The measurement of secondary magnetic field can be obtained by several method. Previously phase shift method used where the primary magnetic field need to be subtracted from superimposed of primary and secondary magnetic field measured [3]. Phase measurement is a process of defining the phase deviation between two periodic signals, the input signal and the reference signal. The phase shift measurement is proportional to the conductivity of tested sample and its frequency signal [2].

The alternative way is by using gradiometer (Figure 2) where transmitter or excitation coil is placed equidistant between two sensing coils (receiver) and the sample placed in front of sensing coil. The transmitter coil provides current flow where it induces eddy current and produce secondary magnetic field. Primary and secondary field superimpose and produce electromotive force (emf) detected by sensing coil. The antiphase connection of sensing coils causes cancellation of induced voltage from primary magnetic field thus remains desired voltage from secondary magnetic field. The changes in the distance between sensing coil sample produce different measurement of voltage given by quasi-static approximation of the emf [1].

![Figure 2. Coaxial gradiometer](image2)
2. Methodology
The simulation of single channel magnetic induction spectroscopy was done using COMSOL Multiphysics software. Figure 3 shows step-by-step of the process to detect the voltage of blood which represents the pH value either normal \((pH \geq 7.25)\), border line \((pH \ 7.21-7.24)\) or abnormal/acidosis \((pH \leq 7.2)\) [9].

![Flowchart](image)

**Figure 3.** Process to detect the voltage of blood flowchart

The simulation of MIS for fetal acidosis was started by designing the probe, scalp model and fetus. The silicon probe with length of 8cm and diameter 1cm [10] consists of two coils transmitter (TX) and
receiver (RX) made up of copper. They are both circular coil with cross-section diameter of 0.02cm. Number of turns, \( N \) were 5N and 10N which resulting a diameter size of 0.6cm and 0.7cm for TX and RX coil respectively. Both coils were designed perpendicular to each other with distance of 0.05cm [11] as shown in Figure 4. Distance of coil RX coil to the scalp was fixed to 0.5cm [11],[12] from the RX edge or equal to 0.85cm from center of RX to the scalp.

![Figure 4. a) Coil design 90° TX-RX b) Probe positioning at the fetal scalp](image)

The fetal scalp dimension in Figure 4 was set to diameter 10cm which is the average size for normal fetus. The scalp was assumed only contain blood with the passive electrical properties values set to permittivity 155, permeability 1 and conductivity 1.95m\(^{-1}\) [3],[13]. The supply frequency range started from 1 to 20MHz and being tested with input 1A. A passive transimpedance circuit (Figure 5 a) consists of one resistor (1m\(\Omega\)) was connected to RX which acts as current to voltage converter where the voltage is measured through the resistor. This model has been tested with 10 pH values from 6.5 to 7.4 which represents acidosis to normal condition. The respective conductivity values [3] were set as shown in Table 1. The procedure was replicated for 1V input at the TX coil and the results were compared.

![Figure 5. Transimpedance circuit a) Passive b) Active](image)

| pH  | 6.5 | 6.6 | 6.7 | 6.8 | 6.9 | 7.0 | 7.1 | 7.2 | 7.3 | 7.4 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(\sigma\) (S/m) | 1.9 | 1.8 | 1.7 | 1.6 | 1.5 | 1.4 | 1.3 | 1.2 | 1.1 | 1.0 |
3. Results and Discussions
Modelling and simulation of MIS design for fetal acidosis is discussed based on the type of transmitter input, range of frequency used, receiver coil voltage and its associated pH values.

Firstly, TX coil was set up 90° to the RX (Figure 4) which produced voltage measured at RX for conductivity 1.9 S/m (pH 6.5) as shown in Table 2. Voltage recorded in the receiver coil is proportional to the rate of change of magnetic flux through the coil $\Delta B$. Voltage have real and imaginary components representing the permittivity $\varepsilon$ and conductivity $\sigma$ of the sample respectively [14] as shown in equation (1). The secondary magnetic field directed in the opposite direction to the external primary magnetic field of the TX coil, thus induced current in receiver (Lenz’s law).

$$\frac{\Delta V}{V} \propto \omega(\omega \varepsilon_r - j\sigma)$$

Perpendicular coil positioning has successfully eliminated the readings from primary magnetic field at the receiver. 1A input recorded lower induced voltage (0.01mV) compared to 1V input (0.1mV) however reduces to (0.06mV) as frequency increases. The voltage received was very small in millivolts for input 1A and 1V. This is supported by the previous study where the inductive sensors are sensitive only to the flux that is perpendicular to their main axis [11]. Thus, this design become straightforward which could directly obtain voltage of secondary magnetic field through passive transimpedance circuit with only 1 resistor (1mΩ) without additional phase shift method or gradiometer technique.

The input current 1A is known as hazardous that may cause organ damage and burn. In this study, 1A input current was used to observe the performance of MIS probe since the induced voltage gain is about 100 times smaller or even more as observe in Table 2. This is due to low conductivity of biological tissue usually less than 2 S/m. In final probe design, the current will be reduced to a very small value but enough to generate eddy current and detect the significant difference of voltage measurement as the conductivity varies.

| Freq (MHz) | RX Voltage for Input 1A (mV) | RX Voltage for Input 1V (mV) |
|------------|-----------------------------|-----------------------------|
| 1          | 0.11802800823841            | 1.0754333637306             |
| 2          | 0.09183916401708            | 0.56724937720482            |
| 3          | 0.08286618031910            | 0.3896544577050             |
| 4          | 0.07621075082048            | 0.29834662807060            |
| 5          | 0.07025062612424            | 0.24226352668877            |
| 6          | 0.0648390332565             | 0.20412690380585            |
| 7          | 0.05997625281496            | 0.17643316294183            |
| 8          | 0.05564052977225            | 0.15537728873279            |
| 9          | 0.05178649298509            | 0.13881425285974            |
| 10         | 0.04836024305636            | 0.12543852143651            |
| 11         | 0.04530810298571            | 0.11440805694457            |
| 12         | 0.04258088140477            | 0.10515454766592            |
| 13         | 0.040135322945416           | 0.09728009387136            |
| 14         | 0.03793395632263            | 0.09049764141994            |
| 15         | 0.03594503459654            | 0.08459474179865            |
| 16         | 0.03414117708480            | 0.07941079712241            |
| 17         | 0.03249938252263            | 0.07482206447836            |
| 18         | 0.03100017040657            | 0.07073167444828            |
| 19         | 0.02962638994927            | 0.06706297374443            |
| 20         | 0.02836375732675            | 0.06375326719274            |
Figure 6 and Figure 7 show the changes of RX voltage due to different input frequency from 1MHz to 20MHz for pH 6.5 and 7.4. High frequency above 10MHz is used to observe the interaction between magnetic field and the scalp tissue. Voltage at RX is results from eddy current in sample which is directly proportional to the secondary magnetic field. Both figures show decreasing voltage from 1 to 10 MHz. However, the difference only can be observed at 7th decimal places; e.g. at 1MHz the voltages were 1.39884636895883mV and 1.39884641323251mV for pH 6.5 and 7.4 respectively. This result the overlapping plot for all pH values from 6.5 to 7.4 as shown in Figure 6. However, the significant difference can be observed in a high voltage resolution plot.

![Input 1A Voltage vs Frequency](image1)

**Figure 6.** Voltage versus frequency graph for 1A input

For 1V input shown in Figure 7, the graph become saturated above 10MHz to almost 0mV as frequency increase. The saturation of dielectric occurs due to intense fields where polarized sidechains of macromolecules align with the field, leading to a possible breakage of hydrogen bonds [15]. Thus, frequency more than 10 MHz is not suitable to be used. This is supported by Industrial, Scientific and Medical (ISM) band where the frequency is limit up to 13.56 MHz which categorized as a high frequency (HF). In study [2], phase measurement technique shows that 10MHz was proved as the best frequency due to a very huge different in phase shift between each pH values which indicates high sensitivity.

![Input 1V Voltage vs Frequency](image2)

**Figure 7.** Voltage versus frequency graph for 1V input
Other study [11] observed that frequency is directly proportional to the induced voltage measured at receiver circuit. As the input frequency increases, the conductivity of blood increases which generates higher eddy current thus higher voltage was measured at the RX coil.

Figure 8 shows the graph voltage versus pH for input 1A with 10MHz input frequency from acidosis region (pH 6.5) to normal (pH 7.4). The induced voltage is inversely proportional to the pH value from 0.048365mV to 0.048356mV which follow the theory of relation between pH and voltage. However, it was previously contradicted for the voltage versus frequency graph.

For input 1V, the voltage versus pH graph for 10MHz was plotted as shown in Figure 9. The induced voltage is directly proportional to pH value with a very small difference at $10^{-9}$mV. The other frequencies from 1-20MHz also show the same pattern of graph. This result is opposite to the theory of lossy material which is voltage reduces as pH increases due to the properties of blood conductivity [2]. In addition, 1V input is not suitable to be used since the changes of voltage at an instantaneous pH value was too small. In experimental, this will require a very good amplifier and the signal will be easily distorted by noise.
4. Conclusion
Design of perpendicular coil TX and RX was able to detect only secondary magnetic field created by the blood of fetal scalp. The voltage has inversely proportional relation to the pH, although has failed to meet the theory of voltage directly proportional to the frequency. The MIS phase shift technique was simplified by implementing the perpendicular design as the secondary magnetic field can be obtain without need to calculate the emf quasi-static approximation and also the influence of residual voltage due to non-ideal symmetry of gradiometer coil which have trade-off between the sensitivity and the noise level [11]. In future research, this model need to be tested using a frequency range up to 10MHz, a smaller input current (<1A) and implementing an open loop sensing in COMSOL software [1].

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