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SINGLE CHANNEL MAGNETIC INDUCTION SPECTROSCOPY TECHNIQUE FOR FETAL ACIDOSIS DETECTION

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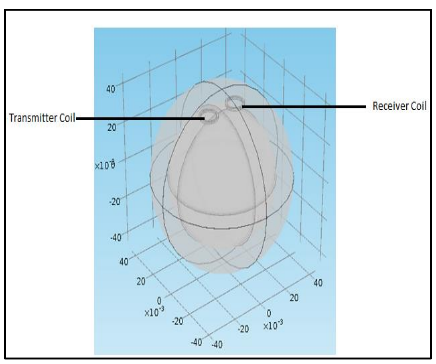
Graphical abstract



Abstract

Current fetal acidosis diagnosis needs an invasive measurement which required a doctor to puncture fetal scalp to acquire blood pH. This method introduced risk to the fetal which fetal scalp may bruise and infected. This paper discusses a noninvasive method employing a single channel magnetic induction spectroscopy technique as an alternative method to diagnose acidosis in fetal without puncturing the fetal scalp. The studies are based on numerical simulation models to investigate the most feasible sensor coil that is sensitive and effective to be implemented in hardware setup as the shape of coil influences directly the sensing performance of the magnetic induction spectroscopy system. The study has found that the circular coil is more sensitive than linear coil. The system tested with different pH samples to mimic the blood pH value. The result is very promising with good correlation approaching 1 has been achieved. Therefore, magnetic induction spectroscopy technique has good opportunity to be applied as an alternative method to detect acidosis in the fetal with circular coil is performed as the best sensing coils for MIS hardware.

Keywords: Fetal acidosis, single channel magnetic induction spectroscopy, blood pH, coil sensing performance, magnetic field, COMSOL Multiphysics

1.0 INTRODUCTION

Acidosis is a condition where the concentration of hydrogen ions in the tissue is high [1]. When this condition occurs, it leads to cellular hypoxia or in fetal case, fetal hypoxia or intrauterine hypoxia. Intrauterine hypoxia can be defined as the condition occur when the fetus is deprived an insufficient oxygen [2]. One of the techniques to detect this symptom is by fetal blood scalp sampling (FBS). This procedure executed in active labor. The purposes of this testing are to prevent unnecessary intervention by investigation of pH and lactate.

FBS is the crucial assessment before labor to determine the oxygen level of the fetus over blood pH. This test helps to identify the suitable technique to deliver the baby, either by normal birth or caesarean method [3], [4]. Conventional techniques for this test requires the small incision on the fetal scalp and a few drops of blood is collected using a thin heparinized capillary tube [5] as shown in Figure 1.

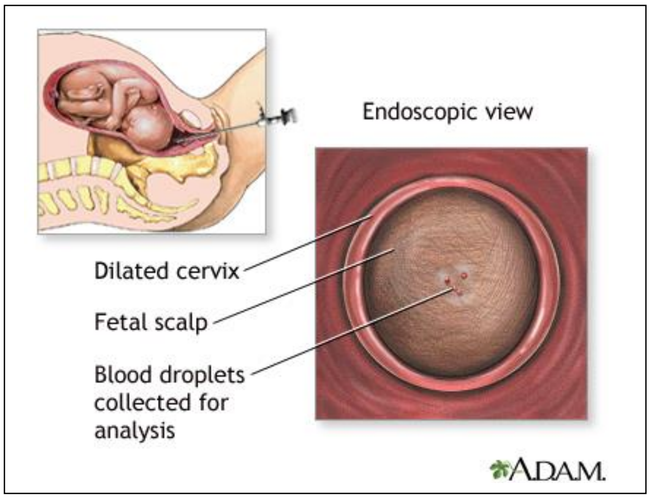


Figure 1 FBS procedure [6]

The blood collected is then taken to the lab for analysis, which consuming time [7]. Furthermore, pitfall may occur during this invasive method, such as inadequate incision, which may lead to continuing bleeding [8]. This condition is very dangerous to the fetal and arise trauma to the mother. Besides that, the analysis of pH requires a relatively large amount of blood (30-50ul) and sampling failure rates of 11-20% have been reported [9]. After considering all the risks, a noninvasive of FBS technique is proposed as an alternative to this conventional method.

Single magnetic induction spectroscopy (MIS) setup is proposed as the non-invasive technique to detect low conductivity of biological tissue. The MIS setup is a non-invasive technique which claims that is it uses a magnetic field to determine or aiming passive electrical properties (PEP) conductivity, permittivity and permeability of biological tissue at different frequencies [10]. However, conductivity is the key element in the measurement as it relates directly to the fetal acidosis [11], [12]. MIS has an ability to detect an object by using a multiple-frequency and induced magnetic fields which are applied through the system to get different output wave due to the interaction between different materials through the samples. This single channel spectroscopy consists of one transmitter and one receiver. The AC signal is supplied to the transmitter and generate primary field. After the fields penetrate into the object with conductivity, eddy current will induced. Figure 2 shows the typical principle of MIS setup.

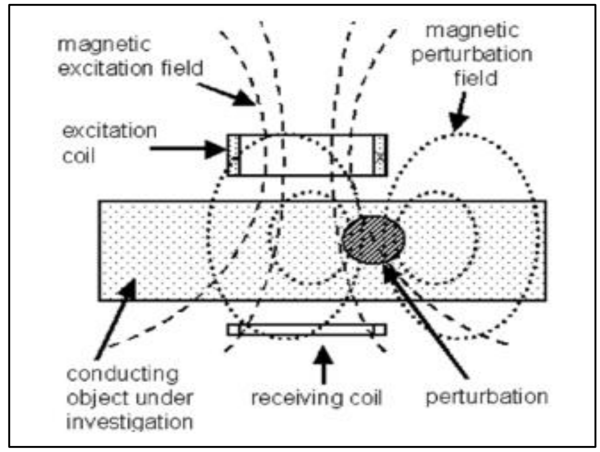


Figure 2 Basic MIS setup [13]

The study of electromagnetic field involves Maxwell's equation [14]. From that equation, when electromagnetic is penetrating a sample, induced eddy current are created by the material itself. This occurs because of electrical properties of the sample is passive [15], [16]. The magnetic field is increasing when the value of the conductivity is increase.

$$\nabla \times E = -j\omega \boldsymbol{B} \quad (1)$$
$$\nabla \times \boldsymbol{H} = (\sigma + j\omega\varepsilon)\boldsymbol{E} \quad (2)$$
$$\nabla \cdot \boldsymbol{D} = \rho \quad (3)$$
$$\nabla \cdot \boldsymbol{B} = 0 \quad (4)$$

The interaction between matter and radiated energy had been a main interest by researchers nowadays. Numerous researchers focus on utilizing diverse technique to simulate this interaction, however the Magnetic Induction Spectroscopy (MIS) is preferred as it eliminates some difficulties with the use of fully non-contacting inductive coupling between the sensor and the sample or in this case biological tissue [17]. Besides that, the magnetic field can penetrate more deeply compare to electrical field [18].

This simulation is focused on the magnetic field in the receiver coil. The aim of this simulation is to test which type of sensor coil is more sensitive and effective to be implemented in MIS hardware setup. Two shapes of sensor coil are tested, which are linear coil and circular coil. The conductivity value of the blood is altered based on pH value. The sensor design also influenced the sensing performance of the system to detect the pH value of the blood scalp, as different inductive coil shapes give different sensing performance sensitivity and linearity characteristic.

Barba *et al*. [19] had reported the used of cone-type screen coil to focusing the electromagnetic (EM) field to the region of interest (ROI) while minimizing the inference effects of the field to the electronic circuit system, while Zakaria *et al.* [20] had compared the performance of C-type and cone-type in their study. It reported that both of the coil design are fitted in centering the EM field to the ROI and in the meantime lessen the scattered EM field to the nearby system. Besides that, Zakaria *et al.* [15] also reported that C-type coil may fully eliminate the scattering effect at the certain frequency.

Misron *et al.* [21] studied about the effect of inductive coil shape on sensing performance of linear displacement sensor using thin inductive coil and pattern guide. They reported that inductive coil with square shape gives a very good sensor performance, while the circle coil shape produce highest sensitivity of 3.4 mH/cm, with the linearity being less than 80%. The performance of the coil can be increased with large number of turns, however, it can reduce the sensor sensitivity. They conclude that the suitable inductive coil pattern needs to be appropriately selected based on required application.

In MIS setup, the permeability or conductivity of the biological tissue should be considered, whereby the blood capillary, the amniotic fluid, vascular and also other vital organ has its own permeability and conductivity. The capillary permeability is specified by the exchange of nutrients, metabolites and breathing gases and the vascular permeability are based on the intimal endothelial cells permeability which is the endothelial binding can change drastically in a short time [22]. Thus, by considering all those biological tissues, this will help in finding the pH value of the fetal scalp by using MIS.

In the previous study, in term of medical field biological processes within the human body require a narrow range of pH for normal function, and significant changes of pH from this reach might be life threatening [23]. Thus an accuracy and stability of the pH estimation framework should be disclose to overcome these issues. One of the methods that had been proposed is by utilizing a hyperpolarized carbon dioxide and bicarbonate as a medium to gauge the intracellular pH in the heart. The implemented of magnetic resonance spectroscopy (MRS) to quantify the pH value of the blood in the heart. From the reading, there are limitation on this method which is hyperpolarized will not directly distinguish between the metabolites that are located in the intracellular and also in the extracellular spaces [24]. Likewise from the previous study state that by using MRS, to measure a cardiac pHi in vivo are not possible due to 2,3-diphosphoglycerate (2,3-DPG) in the ventricular blood contaminates the myocardial inorganic phosphate peak. Therefore, these will be some restriction to this method which is cannot to be utilize in real-time to measuring a pH in human intracellular.

Amniotic fluid is a protective liquid in the amniotic sac of the pregnant female. Amniotic fluid has its own pH with the mean value of 7.1 Unnoticed contamination of the small amount of the fetal scalp blood sample with amniotic is possible. Fetal blood pH rises immediately when it contaminated with amniotic fluid [25]. Furthermore, the amniotic fluid pH will be more acidic when we compared to the uncontaminated blood pH. The pH value of both amniotic fluid and fetal blood will changes when the oxygenation happens, thus by considering this will be more useful in order to determine accuracy of the system.

2.0 METHODOLOGY

The simulation of single channel biological tissue spectroscopy was done using COMSOL Multiphysics software.

Two shape of sensor design is tested, which are linear coil sensor design and circular coil sensor design. These shape of coils is default in COMSOL simulation [26], which can be selected in the coil type icon. The coil is used to generate a magnetic field and specification of it is very important to generate strong magnetic fields to cross the region of interest and detect the properties of the sample by using the principle of MIS [27]. Therefore, we used 5 turns coil for transmitter coil and 10 turns coil for receiver coil with applied current of 1A to excite the coil. The inductance value for linear shape of the transmitter and receiver coil are 1.15mH and 3.75mH respectively, while for circular shape are 0.315μH and 0.175μH. In this simulation model, the transmitter coil and receiver coil located side by side. The material used for the coil is copper. The detail specification of the coil is shown in Table 1.

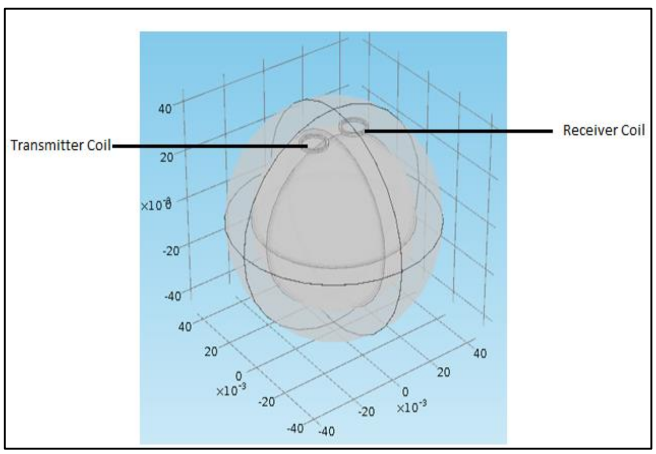
Table 1 Properties of the coil

No		Properties	Transmitter Coil	Receiver Coil
1	Linear Coil	Number of turns	5 turns	10 turns
2		Diameter of the coil	5mm	5mm
3		Diameter of the wire	1mm	1mm
1	Circular Coil	Number of turns	5 turns	10 turns
2		Diameter of the coil	5mm	5mm
3		Diameter of the wire	1mm	1mm

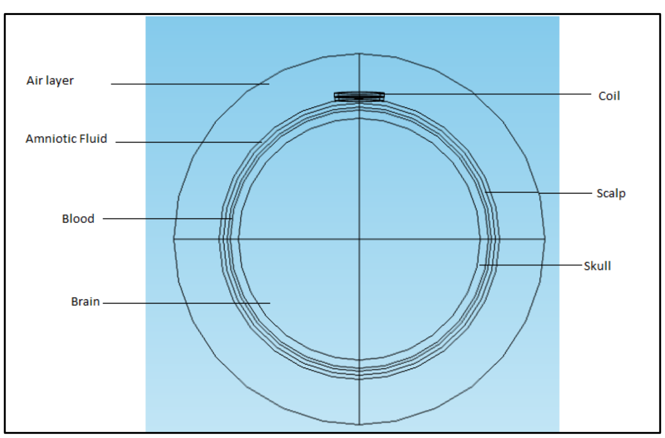
The properties of the material consist of amniotic fluid, biological tissue (in this case scalp), blood, skull and brain [28]–[32]. The frequency used is 10MHz, in the range of β-dispersion.

By using COMSOL Multiphysics, the transmitter is designed to produce a magnetic field across a sample which contains an amniotic fluid, scalp, blood, skull and brain in it. The magnetic field must in the form of perturbation of voltages and it is induced in receiver coil [33]. The signal will be simulated and modelled by using COMSOL Multiphysics. MIS requires an alternating magnetic excitation field to make the measurement of radiation intensity from the excitation coil to the biological soft tissue under investigation. Whereas, the changing in the complex conductivity will make a change in the relative magnetic permeability in the output, caused by the perturbation due to the radiation intensity coupled from the interaction between matter and radiated energy as a function of wavelength in the object under investigation [12], [13], [34].

The diameter and thickness of the fetal head model is assuming as the exact model of cranial structure [35]. This is to help to increase the accuracy of the simulation. Figure 3 show the main part of the system designed which are the coils, sample and the air around the system for accurate result.



(a) Overall view



(b) Layer view

Figure 3 MIS setup in COMSOL Model

The conductivity value of the blood is altered as shown in Table 2. This is to detect whether the system is able to detect the smallest changes in pH blood through conductivity value.

Table 2 Conductivity of pH in blood

pH	σ (S/m)
6.5	1.9
6.6	1.8
6.7	1.7
6.8	1.6
6.9	1.5
7.0	1.4
7.1	1.3
7.2	1.2
7.3	1.1
7.4	1.0
7.5	0.9

3.0 RESULTS AND DISCUSSION

The simulation begins with a simulation of cranial model with linear coil. The magnetic field received in the receiver is plotted in Figure 4.

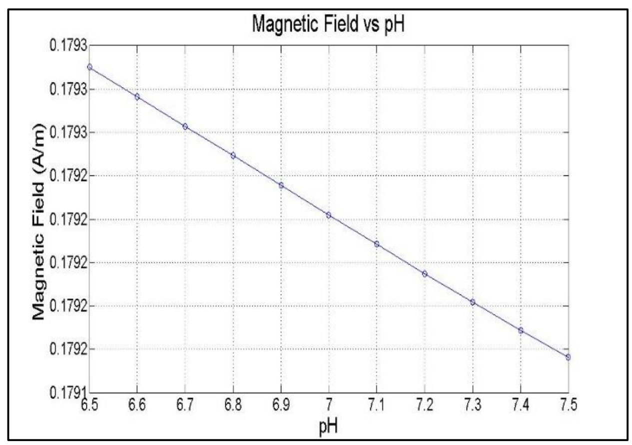


Figure 4 Magnetic field results for linear coil sensor design

The simulation is continued with simulation with circular coil. The result of magnetic field received at the receiver coil is plotted as shown in Figure 5.

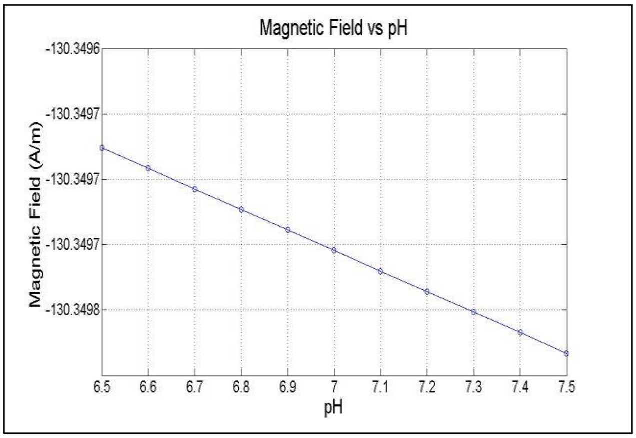


Figure 5 Magnetic field results for circular coil sensor design

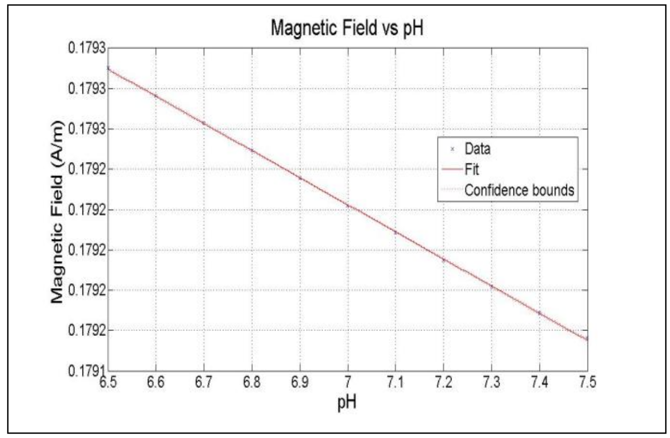


Figure 6 Linear regression of linear coil

From Figure 4 and Figure 5, the results show that as the pH increases the magnetic field decreases. For linear coil, the magnetic field is decreasing with increasing pH. Increase in pH result decreasing in conductivity value. The magnetic field produce is depending on the conductivity value of the blood, which fulfill the Maxwell's Equation [15], [16] mention in the introduction section.

The circular coil result shows the same pattern as linear coil. However, the magnetic field that received at the receiver is in negative value. This negative value exists because the secondary field produced is opposed the direction of the primary field.

The magnetic field received at the circular sensor design is higher than the linear sensor design. This is because circular coil is more sensitive compare to linear coil. The receiver measures the sum of the primary and secondary fields or it measures associated voltage. So, if the value of the receiver is high, it means that it receives more secondary field. The conductive host of the model also influenced the magnetic field that received at the receiver. The primary field becomes altered as it is penetrating into the body.

Linear regression of both results is then plotted. Mathematical derivation and correlation, R^2 is acquired. The linear regression of linear coil is shown in Figure 6 and linear regression of circular coil is shown in Figure 7.

The mathematical derivation and R^2 is as follows:

$$y = 0.00013x + 0.1802 \quad (1)$$

$$R^2 = 1 \quad (2)$$

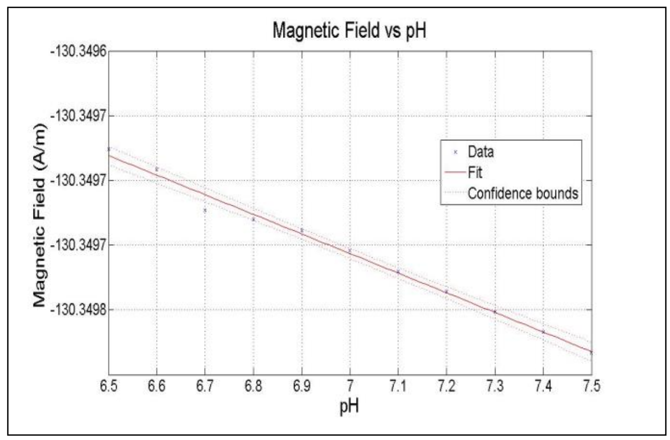


Figure 7 Linear regression of circular coil

The mathematical derivation and R^2 is as follows:

$$y = 0.0002x - 130.34.87 \quad (1)$$

$$R^2 = 0.99 \quad (2)$$

Both results show good correlations which are 0.99 for linear coil and 1 for circular coil. Poor correlation will be less than 0.7. The mathematical equation that derived can be used to calculate the magnetic field received at the receiver when the conductivity value of the blood is unknown.

Fetal blood during invasive technique has a risk to be contaminated with amniotic fluid. When this occurs, the pH value of the blood is increase compared to uncontaminated blood. So, in MIS setup, the dielectric properties of amniotic fluid also affect the final reading of induced current and secondary field receives at the receiver.

4.0 CONCLUSION

Based on simulation above, MIS setup has a capability to be an alternative method to conventional FBS method. The circular coil is chosen as the best performance to be implemented in the MIS setup because it has good sensitivity compared to linear coil in order to detect pH of scalp blood. With the correlation approaching 1, there is a significant positive relationship between the pH value and magnetic field. The potential of this setup to detect the smallest changes of in the pH solution makes it an excellent non-invasive technique. For future work, MIS setup will be developed to validate equation acquire in the simulation, thus prove the accuracy of the system.

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