A New Era in Fetal Monitoring: The Promise of Bio-Impedance Techniques

Ramesh Kumar[1], Vivekanandam1, Rajesh Dey[2]
[1]Lincoln University College, Darul Ehsan, Malaysia
[2]Gopal Narayan Singh University, Sasaram, Bihar, India 821305
(rameshkumarmeena@gmail.com, vivekanandam@lincoln.edu.my, rajesh.dey@gnsu.ac.in)

Abstract: The fetal monitoring approach holds critical importance in obstetrics, as illustrated by a review covering techniques from basic fetoscope auscultation to sophisticated electronic fetal monitoring (EFM) used in engineering. This constant surveillance during labor is essential for rapidly detecting signs of fetal distress, ensuring timely interventions for safe outcomes. Furthermore, this research presents an innovative, noninvasive, user-friendly, and cost-effective bioimpedance-based fetal monitoring system , making it suitable for mass healthcare, including use by impoverished populations and basic health workers. Ultimately, the review emphasizes the necessity of standardized protocols, continuous research, and healthcare professional training to maximize the accuracy and effectiveness of these monitoring methods.

Keywords: Electrical Impedance Techniques (EIT), Feto- maternal monitoring, Tomography, Imaging, Monitoring

---

Introduction

The evolution of fetal monitoring technology has significantly advanced the evaluation of fetal health during pregnancy and labor. From simple auscultation techniques to sophisticated computerized systems, these advancements have revolutionized prenatal care. Modern monitoring systems, incorporating technologies like fetal pulse oximetry and advanced algorithms, provide real-time data to healthcare professionals, enabling informed decision-making during labor.

While traditional methods like ultrasound and cardiotocography are valuable, they can be invasive and uncomfortable for patients. To address this, researchers are exploring non-invasive techniques, such as electrical impedance, to continuously monitor fetal parameters. By analyzing changes in electrical impedance due to fetal movements and other factors, this method offers a potential solution for more patient-friendly and effective fetal assessment.

Pregnancy necessitates significant physiological adaptations in the maternal system to accommodate the developing fetus. This complex process involves a delicate balance of immune tolerance, suppression, and modulation to ensure a successful pregnancy. The maternal-fetal interface is a dynamic system influenced by endocrine and immunological factors. Dynamic systems theory offers a valuable framework for understanding fetal development. This approach recognizes the interconnectedness of various bodily systems and their impact on the fetus's anatomical, physiological, and behavioral characteristics. As pregnancy progresses, the maternal body undergoes substantial anatomical and physiological changes, affecting organs such as the uterus, cervix, vulva, vagina, and ovaries.

EIT provide a non-invasive method for evaluating tissue characteristics. Changes in tissue structure and composition, often associated with pathological conditions, can alter electrical impedance. This principle suggests that pregnancy-related changes in fetal tissues may be detectable through electrical impedance measurements. By studying dynamic phantoms, researchers can investigate the potential of this technique to monitor fetal development and identify potential abnormalities.

Literature Review

Based on the current literature review, we conclude that the future potential of the Electrical Impedance Tomography (EIT) technique lies in several key advancements. Primarily, there is a strong focus on generating enhanced images through improvements in both hardware and software algorithms. Secondly, increasing the number of electrodes used is expected to significantly improve the image resolution. Crucially, EIT could be adapted for long-term fetal monitoring. Finally, the technique should be leveraged to enable the evaluation of morphological and physiological parameters directly from the acquired EIT images and data.

Fetal Monitoring Techniques

Modern medical research is intensely focused on creating innovative, non-invasive, and cost-effective patient monitoring technologies. A major goal is to capture direct bio-signals from the body's surface, which helps reduce healthcare costs while significantly enhancing patient comfort. Consequently, non-invasive techniques have become the established standard in the field of fetal monitoring because of their reliability and suitability for safe, continuous use throughout both pregnancy and labor. While fetal Doppler ultrasound is valuable for assessing fetal health during pregnancy, its sensitivity to movement limitations restricts its use during labor. Concerns about potential long-term effects of continuous ultrasound exposure have further prompted the search for alternative, non-invasive monitoring methods. Fetal monitoring is a crucial procedure to assess fetal well-being during pregnancy, labor, and delivery. It involves tracking fetal movements and uterine contractions. Both internal and external monitoring techniques are employed to gather this essential information.

Internal monitoring involves inserting a thin wire electrode into the uterus, attaching it to the fetal scalp. This invasive procedure allows for direct measurement of the fetal heart rate, but it can be uncomfortable and carries potential risks, especially after the membranes have ruptured. External monitoring is a non-invasive technique that uses external sensors placed on the mother's abdomen. These sensors utilize ultrasound technology to detect fetal heart rate and uterine contractions. While less invasive, external monitoring may be less accurate, particularly in cases of maternal obesity or fetal positioning. Abdominal recordings, a non-invasive method, involve using surface electrodes to measure electrical signals from the mother's abdomen. This technique is safe and comfortable for both mother and fetus, allowing for continuous monitoring throughout pregnancy. By analyzing changes in electrical impedance, it can provide valuable insights into fetal health and well-being.

Electrical Impedance Tomography

The fundamental theory of Electrical Impedance Tomography (EIT) is based on applying a constant electrical current across a substance. The resulting voltage distribution measured on the surface then provides information about the material's internal resistivity distribution. However, it is important to recognize a key challenge: multiple different internal resistivity structures could potentially generate the exact same voltage pattern on the surface. To overcome this ambiguity and accurately map the internal structure, the EIT system is designed to be stimulated in various ways. This process helps to constrain and narrow down the possible internal resistivity distributions. (Figure 2, not provided, typically illustrates a simple EIT setup.)

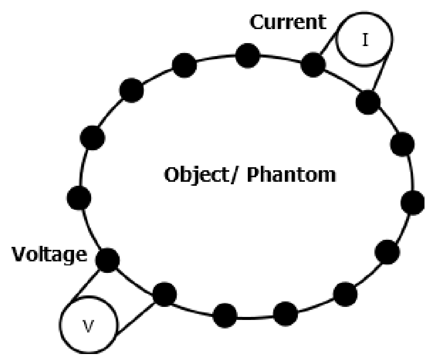


Figure 1. EIT Diagram

EIT is an innovative technique for visualizing an object's internal structure without interfering with its normal operations. Outside of medicine, EIT is applied in various aqueous-based industrial processes, such as monitoring the mixing of miscible liquids, analyzing solid-liquid mixtures, and tracking cyclonic separation. The advantages of EIT are significant: it is non-invasive, economical, non-destructive, radiation-free, and inherently focused on visualization. In the field of medical imaging, EIT is specifically used to create images that map the conductivity or permittivity of specific regions of the body. To facilitate this imaging procedure, conductive electrodes are typically attached to the subject's skin, and small alternating electrical currents are injected through a select few of these electrodes, while the resulting voltages are measured on the others.

A. Method of Data Acquisition

In Bio-impedance and Electrical Impedance Tomography (EIT), several electrode strategies are employed to measure internal resistivity. The Neighboring method injects current between adjacent electrodes and measures voltage sequentially across other adjacent pairs, yielding $N(N-3)$ measurements for N electrodes. Conversely, the Opposite method injects current between opposing electrodes, uses an adjacent electrode as a reference, and measures voltage on the remaining electrodes, producing a uniform current distribution and high sensitivity (e.g., 104 data points for 16 electrodes). The Cross method injects current between farther-apart electrodes to ensure a more even current distribution and higher whole-region sensitivity. Relatedly, Impedance Plethysmography (IPG) assesses changing tissue volumes by analyzing surface electrical impedance measurements.

Hardware- Software

This study centers on the experimental application of EIT for feto-maternal monitoring, where I built a system to acquire morphological and physiological data for subsequent image reconstruction, summarized by a top-view block schematic. The EIT system integrates an electrode array (sensors), specialized digital and analogue circuits (including precision current sources and data capture components, potentially utilizing a PSoC or microcontroller), and a PC for data processing. Image reconstruction relies on mathematical algorithms that initialize a conductivity value, calculate estimated potentials, and compare them against measured potentials. This process uses the Finite Element Method (FEM) mesh (comprised of triangular elements) to solve the forward problem—calculating potentials based on a known current pattern, magnitude, and assumed homogeneous medium conductivity—which is essential for accurately mapping the internal resistivity.

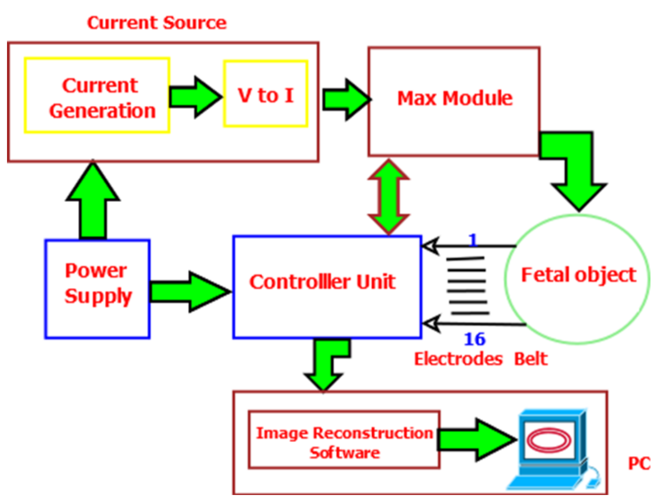


Figure 3: EIT Block diagram for fetal monitoring

B. Experimental Work

Fetal well-being monitoring is a crucial aspect of prenatal care. Various techniques are employed to assess fetal health, including bioimpedance methods such as IPG and EIT. IPG is a non-invasive method that measures changes in thoracic impedance to assess fetal breathing movements. By detecting variations in impedance caused by chest expansion and contraction during breathing, IPG can provide insights into fetal respiratory function. Deviations in breathing patterns may indicate potential fetal health issues.

C. Experimental Work for Feto-maternal Monitoring

This experimental validation will involve comprehensive phantom analysis using both dynamic and static systems to test the Electrical Impedance Tomography (EIT) and Impedance Plethysmography (IPG) techniques. We will begin by constructing a dynamic phantom designed to closely mimic the properties of the human uterus. Subsequently, we will calculate the impedance distribution of this phantom using both EIT and IPG. The analysis will systematically explore different configurations, specifically varying the number of electrodes (e.g., 2, 4, 8, or 16) and the current acquisition methods (Neighboring, Opposite, and Cross methods) used in EIT. The ultimate goal is to evaluate the morphological and physiological parameters related to the fetus based on the data acquired from these detailed phantom experiments.

D. Impedance Plathysmography based Results

In our experimental procedure, the excitation current was initially applied to electrodes $\text{E}1$ and $\text{E}3$. The resulting voltage was then measured as the potential difference between electrodes $\text{E}2$ and $\text{E}4$, completing the first measurement configuration. The current and voltage measurement locations were then swapped: the current was applied to electrodes $\text{E}2$ and $\text{E}4$, and the voltage was measured across $\text{E}1$ and $\text{E}3$, establishing the second configuration. The impedance values obtained from both of these complementary measurements are presented in the subsequent Table 1 (not provided).

Table 1. Experimental on different phantoms through IPG

S. No.	4	2	7	3	9	5	6	1	8
Experimental Phantoms	Orange	Cabbage	Human body	Onion	Plastic box	Capsicum	Red chili	Potato	Papaya
Impedance of 1st position (E2 & E4)	1.77mv	2.31mv	0.3 mv	1.72mv	4.38mv	3.5mv	0.64mv	1.55mv	1.15mv
Impedance of 2end position (E1 & E3)	2.2mv	2.34mv	0.42 mv	2.15mv	3.89mv	3.05mv	2.86mv	0.68mv	1.05mv
Current	0.6 mA 10 kHz and 100 kHz								

Electrical Impedance Tomography based Results

As per the experimental work focuses on phantom analysis to validate the Electrical Impedance Tomography (EIT) technique, utilizing both dynamic and static systems. We will first create a dynamic phantom that mimics the properties of the human uterus. We will then calculate the impedance distribution of this phantom, systematically varying the experimental parameters, specifically the number of electrodes (e.g., 4, 8, or 16) and the current acquisition methods (Neighboring, Opposite, and Cross methods). The EIT imaging approach relies on inferring the internal conductivity distribution from electrical measurements taken on the body's surface; typically, a low-level, alternating current (10-100 kHz, mA range) is introduced via one pair of input electrodes, and the resulting voltages are measured at all remaining electrodes. Following this principle, and due to its ability to successfully imitate the human uterus, sixteen electrodes were strategically placed on the mother's body in a real-world scenario to acquire voltage measurements according to various EIT current patterns, ultimately allowing us to evaluate the morphological and physiological parameters related to the fetus from the acquired data and validate the proposed monitoring strategy.

Figure 4: Experimental Setup for Fetal with Mother

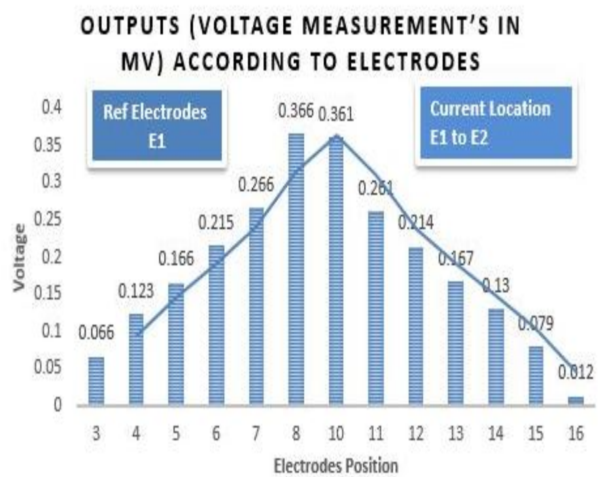


Figure 5: Impedance Distribution for one current location

The impedance distribution graph visually represents the spatial variations of electrical impedance within a specific area, achieved by applying a consistent electrical current to a site and utilizing the resulting measurements at various locations to characterize the tissue's electrical properties. This visualization is highly valuable in medical diagnostics because it facilitates the detection of regions with distinct conductivity or impedance patterns, which may indicate differences in tissue composition, blood circulation, or physiological functioning. It provides a more comprehensive understanding of the internal dynamics and functional attributes of biological tissues or organs at a given location. For instance, data obtained from an experimental setup, like the one used for the stomach, produces two basic output images via the image reconstruction algorithm: Figure 6(A) shows a 2D reconstructed image and Figure 6(B) provides the Contour view of that same image.

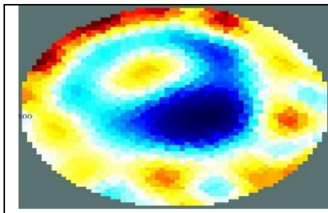
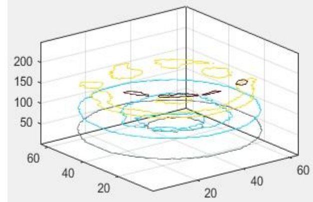
<table>
<tr><td></td><td>
</td></tr>
<tr><td>(A) 2D Image through the Image Algorithm</td><td>(B) Contour View of Image</td></tr>
</table>

Figure 6: Final results

Bioimpedance monitoring techniques have emerged as valuable tools in fetal monitoring. Non-invasive methods like IPG and EIT enable continuous assessment of fetal physiological parameters, such as respiratory activity, tissue perfusion, and blood flow. By providing real-time, objective data, bioimpedance monitoring empowers healthcare providers to identify potential complications early on and intervene promptly. This continuous assessment throughout pregnancy allows for individualized care and optimal outcomes for both mother and fetus.

Bioimpedance monitoring techniques, while promising, face several challenges that limit their widespread clinical application. The complex nature of bioimpedance data interpretation, influenced by numerous physiological factors, requires specialized expertise. Additionally, the high cost and technical requirements of bioimpedance equipment can be prohibitive for many healthcare facilities.

Concussion

Feto-maternal monitoring is crucial for identifying a healthy fetus from a growth-restricted one. Advances in technology have the potential to revolutionize this field. By developing low-cost, portable, and non-invasive instruments, researchers can create a real-time, continuous monitoring system. This system would enable healthcare providers to detect potential issues early on, leading to timely interventions and improved maternal and fetal outcomes. In conclusion, EIT presents a promising non-invasive approach for feto-maternal monitoring. By providing real-time insights into both maternal and fetal physiology, EIT has the potential to revolutionize prenatal care. As technology advances and research progresses, EIT may become a valuable tool in obstetrics, improving the standard of care for pregnant women and their unborn babies. However, further research and development are necessary to fully realize the potential of EIT in this field.

References

1. L. Objectives, “Anatomy and Physiology of Pregnancy,” Matern. Nurs., pp. 208–230, 2006.
2. F. Kovâcs, M. Török, and I. Habermajer, “A rule-based phonocardiographic method for long-term fetal heart rate monitoring,” IEEE Trans. Biomed. Eng., vol. 47, no. 1, pp. 124–130, 2000.
3. R. Vullings, C. Peters, M. Mischi, G. Oei, and J. Bergmans, “Maternal ECG removal from non-invasive fetal ECG recordings,” Annu. Int. Conf. IEEE Eng. Med. Biol. - Proc., 1 pp. 1394–1397, 2006.
4. P. K. Hansen, S. F. Smith, J. Nim, S. Neldam, and M. Osler, “Maternal attitudes to fetal monitoring.,” Eur. J. Obstet. Gynecol. Reprod. Biol., vol. 20, no. 1, pp. 43–51, 1985.

5. G. M. Ungureanu, I. Gussi, and W. Wolf, “Prenatal Telemedicine – Advances in Fetal Monitoring,” in Advances in Telemedicine, no. 6, pp. 97–120.2010.
6. C. Schwarz, “Maternal insertion in electronic fetal monitoring: A case report.,” Br. J. Midwifery, 2014.
7. S. Kumar, S. Anand, and A. Sengupta, “Development of a non-invasive point of care diagnostic tool for fetal monitoring using electrical impedance-based approach,” IEEE Point-of-Care Healthc. Technol., pp. 16–18, 2008.
8. B. Science, “Review Article: Non-Invasive Fetal Heart Rate Monitoring Techniques,” Biomed. Sci. Eng., vol. 2, no. 3, pp. 53–67, 2014.
9. H. Cao, D. E. Lake, J. E. Ferguson, C. a. Chisholm, M. P. Griffin, and J. R. Moorman, “Toward quantitative fetal heart rate monitoring,” IEEE Trans. Biomed. Eng., vol. 53, no. 1, pp. 111–118, 2006.
10. A. Fanelli, M. G. Signorini, M. Ferrario, P. Perego, L. Piccini, G. Andreoni, and G. Magenes, “Telefetalcare: A first prototype of a wearable fetal electrocardiograph,” Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS, pp. 6899–6902, 2011.
11. S. Kumar, S. Anand, and A. Sengupta, “Real-time monitoring of fetus movements and uterine contractions using MEMS acoustic sensor,” ITNG2010 - 7th Int. Conf. Inf. Technol. New Gener., 7, pp. 317–321, 2010.
12. M. D. Velazquez and W. F. Rayburn, “Antenatal evaluation of the fetus using fetal movement monitoring.,” Clin. Obstet. Gynecol., vol. 45, no. 4, pp. 993–1004, 2002.
13. T. K. Bera, “Bioelectrical impedance methods for noninvasive health monitoring: A review,” J. Med. Eng., vol. 2014, 2014.
14. T. K aleksanyan, I Gorbatenko Nikolay, “Development of hardware software complex for electrical impedance tomography of biological objects,” J. aalied Sci. 9, vol. 9, no. 12, pp. 1030–1033, 2014.
15. V. E. Arpinar and B. M. Eyuboglu, “Microcontroller controlled, multifrequency electrical impedance tomograph,” Annu. Reports Res. React. Institute, Kyoto Univ., vol. 3, pp. 2289–2291, 2001.
16. B. Kilic and K. O. R. K. Mehmet, “A Finite Element Method Based Neural Network Technique For Image Reconstruction In Electrical Impedance ImaginG,” Int. Biomed. Eng. days, pp. 100–102, 1997.
17. S. Zhang, G. Xu, X. Zhang, B. Zhang, H. Wang, Y. Xu, N. Yin, Y. Li, and W. Yan, “Computation of a 3-D model for lung imaging with electrical impedance tomography,” IEEE Trans. Magn., vol. 48, no. 2, pp. 651–654, 2012.
18. Z. Cao, H. Wang, and F. Dong, “The Study of a 2D Model and Image Reconstruction Algorithm Based on EIT System,” 2006-Instrumentation Meas. Technol. Conf., no. April, pp. 2323–2326, 2006.
19. M. Stasiak, J. Sikora, S. F. Filipowicz, and K. Nita, “Principal component analysis and artificial neural network approach to electrical impedance tomography problems approximated by multi-region boundary element method,” Eng. Anal. Bound. Elem., vol. 31, pp. 713–720, 2007.
20. S. K. Pahuja, “Electrical impedance tomography-based image reconstruction and feto-maternal monitoring in pregnancy,” Health (Irvine. Calif)., vol. 03, no. 8, pp. 482–486, 2011.