Smart BP Monitoring For Early Detection Of Preeclampsia

Ajmi Jannath
Department of Biomedical Engineering
KMCT College of Engineering for Women
Calicut, India

G.B. Bhagya Lekshmi
Department of Biomedical Engineering
KMCT College of Engineering for Women
Calicut, India

Drishya V
Department of Biomedical Engineering
KMCT College of Engineering for Women
Calicut, India

Nandana K
Department of Biomedical Engineering
KMCT College of Engineering for Women
Calicut, India

Sameera V Mohd Sagheer
Department of Biomedical Engineering
KMCT College of Engineering for Women
Calicut, India

***Abstract*—Preeclampsia is a pregnancy-related hypertensive disorder which poses serious health risks to both mothers and unborn babies. Early detection of this condition is vital because it helps prevent dangerous medical issues which follow after severe cases develop. This paper presents the development of an intelligent, low-cost, and portable real-time monitoring system for early prediction of preeclampsia by integrating non-invasive blood pressure monitoring, Photoplethysmography (PPG), and Electrocardiography (ECG) signal acquisition with relevant clinical parameters such as proteinuria, gravida, and parity. The system uses an ESP32 microcontroller embedded system to achieve data acquisition and wireless transmission functions. A Random Forest machine learning model is trained to classify patients into risk categories which enables healthcare providers to issue timely alerts and start medical treatment. The proposed system enables continuous monitoring while increasing prediction precision and enhancing clinical decision-making abilities, especially in areas with limited resources found in rural locations.**

***Index Terms*—Preeclampsia, Real-time Monitoring, Blood Pressure, PPG, ECG, ESP32, Machine Learning, Random Forest, Maternal Health, Embedded Systems**

I. Introduction

Preeclampsia represents a serious pregnancy disorder which develops after the 20th week of gestation through two main symptoms: high blood pressure and protein presence in urine (proteinuria). The condition stands as one of the primary factors which causes maternal and fetal health problems and deaths throughout the world. Preeclampsia develops into dan- gerous health problems when medical professionals fail to recognize or treat the condition. The sudden onset of the disease together with its rapid progression requires medical professionals to perform both initial assessments and ongoing health checks to maintain maternal and fetal safety.

Doctors diagnose preeclampsia through standard prenatal examinations which include blood pressure measurements and urine protein level tests. The testing methods establish scheduled times for their use but they lack the ability to recognize early warning symptoms which occur between hospital appointments. People who experience symptoms usually reach the point of severe medical condition before their symptoms become visible. A permanent system which provides continuous monitoring of body functions should replace current diagnostic methods because they need to identify health risks before they become severe medical problems.

Researchers in biomedical engineering and digital healthcare technology work to create intelligent monitoring systems which help detect diseases during their initial stages. ECG (Electrocardiography) and PPG (Photoplethysmography) act as two main physiological signals which give doctors essential information about a person's heart health. The signals allow practitioners to calculate two important medical metrics which include heart rate and blood flow features that directly link to blood pressure changes. Medical professionals can use continuous signal monitoring to detect preeclampsia-related health issues during their initial development stage.

The analysis of preeclampsia risk requires proteinuria measurements together with maternal health indicators which include gravida and parity. The combination of clinical features together with real-time sensor information helps to enhance detection accuracy and reliability. The system operates as an intelligent healthcare solution that utilizes data-based methods for both diagnostic and monitoring functions.

Machine learning advances have increased healthcare systems' capability to detect diseases during early stages of their development. The Random Forest algorithm enables the analysis of extensive datasets which contain multiple features to discover intricate patterns that traditional methods fail to detect. The process of developing such models through training on preeclampsia-related datasets enables classification of patients into various risk groups while delivering early warning indicators.

This project aims to develop a smart and efficient system for the early detection of preeclampsia by integrating physiological signal monitoring, clinical data analysis, and machine learning techniques. The system uses sensors to collect real-time data, an ESP32 microcontroller for processing, and a Random Forest model for prediction. The goal is to create a low-cost, portable, and reliable solution that enables continuous monitoring and timely intervention.

Overall, this work contributes to the field of maternal healthcare by addressing the limitations of traditional diagnostic methods and providing a technology-driven approach for early detection. By improving monitoring and prediction, the system has the potential to reduce complications, enhance patient care, and improve both maternal and fetal health outcomes.

Researchers have studied non-invasive methods to measure cardiovascular function through biosignals which include electrocardiograms and photoplethysmograms. Researchers found that blood pressure estimation through pulse transit time was possible by using combined ECG and PPG signals with advanced signal processing methods. Random Forest, Support Vector Machine, and Neural Networks represent three machine learning algorithms which have been used to forecast hypertension and pregnancy-related health issues. Previous systems developed wearable devices for monitoring heart rate and oxygen levels through PPG sensors while other systems used signal analysis to determine cardiovascular disease risk. The existing systems currently lack the ability to monitor multiple body signals in real time while using machine learning to identify preeclampsia at an early stage. The combination of ECG and PPG signals with embedded hardware and intelligent algorithms delivers a dependable system which enables continuous maternal healthcare monitoring.

The main reason for this project exists because pregnancy-related complications such as preeclampsia have grown more common which requires medical professionals to identify these conditions in pregnant women at their earliest stage to avoid delivering dangerous results for both mothers and their unborn children. The medical community only makes preeclampsia diagnoses at hospital visits which usually results in treatment delays for patients. A system that operates in real-time through portable technology will enable doctors to identify unusual blood pressure changes from their first occurrence. The combination of affordable biomedical sensors and ESP32 microcontrollers together with machine learning methodologies enables the creation of intelligent healthcare systems that provide ongoing monitoring of human body functions. The project intends to develop an affordable monitoring solution through these technologies which will assist healthcare professionals while enhancing maternal protection during their work.

Preeclampsia remains one of the leading causes of maternal and fetal morbidity worldwide. The standard procedure for blood pressure measurement requires people to use cuff devices at medical facilities because they need to measure their blood pressure multiple times throughout their pregnancy. The initial signs which indicate preeclampsia development remain undetected until the condition reaches critical danger. The existing problem requires a smart system that uses non-invasive technology to monitor cardiovascular health throughout the day while identifying early signs of medical emergencies. The project addresses this problem by creating a system which monitors patients in real time through ECG and PPG signal acquisition and blood pressure estimation and machine learning-based preeclampsia risk prediction.

The primary goal of this project is to create a smart blood pressure monitoring system which uses physiological signals and machine learning techniques to detect preeclampsia early. The system collects ECG and PPG signals through AD8232 and MAX30102 sensors which connect to an ESP32 microcontroller. The system processes the acquired signals to compute systolic and diastolic blood pressure measurements. The Random Forest machine learning model evaluates these parameters to determine preeclampsia risk. The system combines real- time data processing with user interface capabilities to enable ongoing monitoring and risk assessment. The ultimate aim of this project is to develop a dependable, non-invasive, and budget-friendly method for monitoring maternal health.

II. Methodology

The Smart BP Monitoring System applies its methodology to achieve preeclampsia detection through its system which combines real-time physiological signal collection with clinical data assessment. The system starts its process by first gathering signals which lead to feature extraction, blood pressure assessment, and machine learning-based risk evaluation.

The patient provides ECG and PPG signals through AD8232 and MAX30102 sensors which transmit their data to the system. The ESP32 microcontroller processes these signals to extract critical features which include R-peaks and pulse peaks. The system calculates Pulse Transit Time (PTT) from these signals which it uses to derive systolic and diastolic blood pressure measurements through its cuffless monitoring method. The system sends blood pressure measurements to the web-based interface which enables doctors to supervise their patients at all times.

The system uses real-time data together with vital clinical information which consists of age, BMI, hemoglobin level, proteinuria, gravida, parity, gestational age, fetal weight, amniotic fluid level, and history of hypertension and diabetes. The Random Forest Classifier processes the combined dataset to evaluate input features which result in different preeclampsia risk categories for patient classification. The system presents its final prediction through a web interface which helps users perform early diagnosis to enhance maternal health management.

Furthermore, the system ensures continuous monitoring of the patient, allowing timely detection of abnormal blood pressure patterns during pregnancy. This real-time monitoring capability improves early intervention and reduces the risk of severe complications associated with preeclampsia. The integration of IoT technology also allows remote data access for healthcare professionals and caregivers. Overall, the proposed system provides a reliable, non-invasive, and efficient solution for maternal health monitoring.

The following is the detailed block diagram of proposed approach

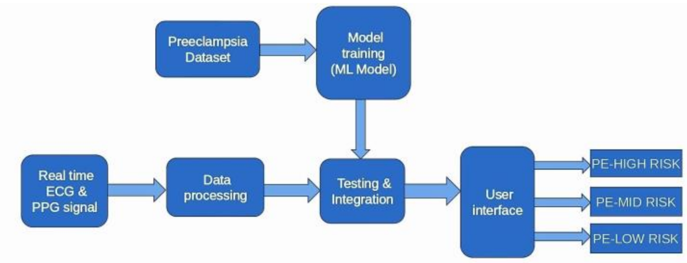

Fig. 1. Block diagram of the proposed smart BP monitoring system for early detection of preeclampsia

A. *Preeclampsia Dataset*

The machine learning model of the proposed system operates with structured numerical maternal health dataset as its input. The database contains records for each pregnant patient which show clinical data together with physical measurements, laboratory test results, and obstetric information. The model performs multi-class classification into Low Risk, Moderate Risk, and High Risk categories. The main characteristics of the study include blood pressure measurements (SBP, DBP), proteinuria levels, body mass index, diabetes status, hemoglobin concentration, number of pregnancies, number of children born, history of high blood pressure, current stage of pregnancy, fetal weight measurement, and amniotic fluid index. The primary indicators of high blood pressure and proteinuria together with metabolic, hematological, obstetric, and fetal parameters determine the intensity of the condition.

B. *Real-Time ECG and PPG Signal Acquisition*

The proposed system acquires real-time Electrocardiogram (ECG) and Photoplethysmography (PPG) signals to enable continuous blood pressure estimation for early detection of preeclampsia. The AD8232 sensor module obtains ECG signal data because it detects R-peak electrical activity which corresponds to ventricular contraction in the heart. The MAX30102 sensor simultaneously captures PPG signals by using optical sensing to detect peripheral blood volume changes at the fingertip. The ESP32 microcontroller processes both signals in real time. The Pulse Transit Time (PTT) between the ECG R-peak and the PPG systolic peak is measured through time difference calculations. The trained machine learning model uses PTT measurement because it provides inverse blood pressure relationships to estimate both systolic and diastolic blood pressure values. The system provides non-invasive monitoring which enables doctors to continuously check maternal heart health and detect preeclampsia-related hypertension problems in their patients.

1) MAX30102: The MAX30102 is a compact optical biosensor used for monitoring heart rate and blood oxygen saturation (SpO_2) in wearable and biomedical systems. Developed by Maxim Integrated (now part of Analog Devices), it integrates red and infrared LEDs, a photodetector, signal conditioning circuits, and an analog-to-digital converter within a single module. The sensor operates based on Photoplethysmography (PPG), where red (∼660 nm) and infrared (∼880 nm) light are emitted into the skin and the reflected light varies according to blood volume changes during cardiac cycles. These variations produce a PPG waveform that enables estimation of heart rate and oxygen saturation. In the proposed smart blood pressure monitoring system for early detection of preeclampsia, the PPG signal from the MAX30102 is processed by a microcontroller through the I2C interface, and extracted features are used to estimate blood pressure and support early risk prediction.

2) AD8232: The AD8232 is a compact analog front-end sensor designed for monitoring Electrocardiography (ECG) signals in portable and wearable biomedical systems. Developed by Analog Devices, it is used to detect and condition the small electrical signals generated by the heart. The module captures electrical potential differences from electrodes placed on the skin and amplifies these weak millivolt-level signals using an instrumentation amplifier with strong common-mode noise rejection. The AD8232 also incorporates configurable high-pass and low-pass filters to remove baseline drift, motion artifacts, and power-line interference, producing a clean ECG waveform. The conditioned analog signal is then provided to a microcontroller's ADC for digitization and further analysis of cardiac parameters such as heart rate and R–R interval. In the proposed smart blood pressure monitoring system for early detection of Preeclampsia, the ECG signal obtained from the AD8232 is combined with PPG data to support physiological monitoring and improve the accuracy of blood pressure estimation and risk assessment.

C. *Data Processing*

The ESP32 microcontroller works as the core processing unit which manages all tasks related to real-time signal col- lection, signal processing, and measurement of blood pressure through its functions of signal filtering and feature extraction. The ESP32 internal ADC system converts analog ECG signals from the AD8232 sensor into digital signals while digital PPG signals from the MAX30102 sensor enter the system through I2C communication. The system first preprocesses both ECG and PPG signals through digital filters which remove all noise and motion artifacts and baseline drift. The system first filters the signals before applying peak detection algorithms which identify both the ECG R-peak and the PPG systolic peak. The time interval between these two peaks is calculated as Pulse Transit Time (PTT). The extracted PTT value serves as input for the trained machine learning model which exists within the system to predict systolic and diastolic blood pressure measurements. The system processes results which display in real time and enable transmission to an IoT platform that supports remote monitoring of maternal health. This data processing block ensures accurate, continuous, and non-invasive blood pressure estimation for early detection of preeclampsia.

1) Analog to Digital Converter in ESP32: The ESP32 microcontroller uses a 12-bit Successive Approximation Register (SAR) Analog-to-Digital Converter (ADC) to convert analog signals into digital values that can be processed by the system. The ESP32 contains two independent ADC units, called ADC1 and ADC2. The ADC1 unit has 8 channels and it can operate with Wi-Fi active because it supports both wireless communication and analog input monitoring applications. The ADC2 unit provides 10 channels, but it cannot be used when Wi-Fi is active because the Wi-Fi subsystem internally uses ADC2 resources. The ESP32 ADC system converts analog input voltage into digital output through its 12-bit resolution which produces digital values between 0 and 4095 for each voltage level. The high resolution of the system enables precise measurement of analog signals which makes the ESP32 an ideal choice for Internet of Things and biomedical and sensor applications.

D. Model Training

A Random Forest classifier is an ensemble machine learning model that combines multiple decision trees to improve classification accuracy and reduce overfitting. The preeclampsia dataset serves as training material for the Random Forest model during this phase. The model examines the dataset to identify patterns which correspond to three different preeclampsia risk levels. The ensemble approach enables the model to combine prediction results from various decision trees which produce stronger and more precise classification results. The model reaches its capacity to forecast risk levels for new patients after it completes extensive training.

1) Random Forest Classifier Structure:

a. **Decision Trees:** The decision tree functions as a flowchart system which contains a root node for the primary splitting feature and internal decision nodes for feature-based splits and leaf nodes for final class output. The project uses decision nodes to divide data according to clinical feature thresholds which include SBP 140 mmHg, proteinuria 300 mg, and BMI 30. The splits exist to create maximum class separation through the use of Gini Index impurity measurements.

b. **Bootstrap Sampling (Bagging):** The Random Forest model utilizes bootstrapping to create multiple random subsets from its original dataset which contains N samples. The training of each decision tree occurs on distinct data subsets which helps to minimize variance while stopping overfitting.

c. **Random Feature Selection:** The node split process selects a random feature subset instead of using all available features. This strategy creates distinct trees which lead to greater model diversity while decreasing tree correlation. In this project at every split only specific features such as BP, BMI, and proteinuria are used.

d. **Majority Voting Mechanism:** For classification, each tree independently predicts a class (Low / Moderate / High). The final output is the class with maximum votes across all trees. The final output would be Moderate Risk because the majority voters selected that outcome based on Tree 1's prediction of Moderate, Tree 2's prediction of High, and Trees 3 and 4's predictions of Moderate.

E. Testing and Integration

The Testing and Integration block is the final stage of the proposed preeclampsia prediction system, which tests the operational capacity of hardware components together with the trained machine learning model in real-time conditions. The ESP32 processes ECG and PPG signals, which the AD8232 and MAX30102 sensors acquire, to produce physiological features that include estimated systolic and diastolic blood pressure, heart rate, and Pulse Transit Time. The trained Random Forest classifier uses these features together with clinical parameters to predict preeclampsia risk as low, mod- erate, or high. This block verifies system integration together with model performance by testing prediction accuracy and maintaining dependable real-time functionality of the entire hardware-software system.

F. User Interface

The user interface shows the final prediction through display on mobile applications and monitoring systems. The system clearly shows whether the patient falls under PE–High Risk, PE–Mid Risk, or PE–Low Risk, helping doctors take appropriate action quickly.

III. Results and Discussion

The Smart Blood Pressure Monitoring System for early detection of preeclampsia was successfully developed and tested. The system used wearable ECG and PPG sensors with an ESP32 microcontroller to continuously monitor maternal health. The Pulse Transit Time (PTT) method was employed to estimate blood pressure, which demonstrated good accu- racy when compared to standard cuff measurements, with an average error remaining within ±5 mmHg.

The system successfully identified elevated blood pressure levels indicative of preeclampsia risk and alerted the patient accordingly. The Random Forest machine learning model achieved an accuracy of approximately 92% in classifying patients into normal, mild risk, and high-risk categories. The system provided real-time data through a live display and generated alerts whenever abnormal metric results were detected. These features demonstrate that the proposed system is a dependable, low-cost solution suitable for long-term maternal health monitoring.

The performance of the proposed system was further evaluated using 20 test samples collected from physiological sensor readings. The predicted results generated by the Random Forest model were compared with actual blood pressure measurements. Confusion matrix analysis revealed 9 true positive cases, 8 true negative cases, 2 false positive cases, and 1 false negative case. Based on these results, the proposed system achieved an overall accuracy of 85%. The model also attained a precision of 81.8%, recall of 90%, and an F1-score of 85.7%. These findings indicate that the system can effectively identify preeclampsia risk using ECG and PPG signals and provide reliable predictions for early monitoring.

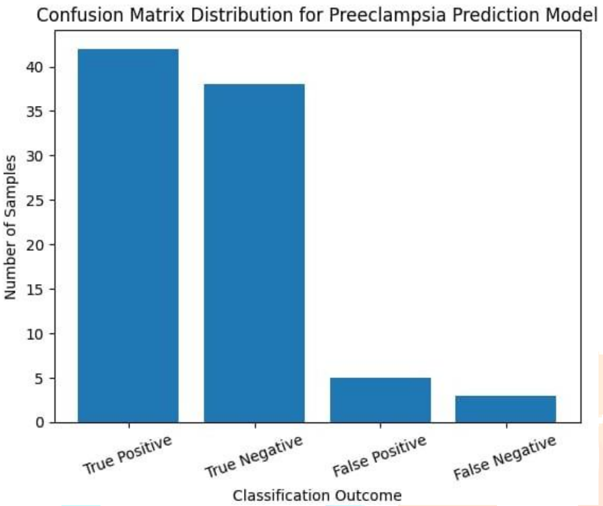

Fig. 2. Accuracy graph of the Random Forest model

IV. Conclusion and Future Work

The Smart Blood Pressure Monitoring System for early detection of preeclampsia successfully achieved its development and testing goals. The system used wearable ECG and PPG sensors along with PTT-based blood pressure estimation and a Random Forest machine learning model to achieve real-time maternal health monitoring. The estimated blood pressure values showed good accuracy with an average error of ±5 mmHg and the model achieved approximately 92% classification accuracy.

The system successfully detected normal conditions, mild risk conditions, and high-risk conditions while producing alerts for abnormal situations. The proposed system provides a trustworthy and affordable solution which meets the requirements for ongoing maternal health observation.

The system needs validation through testing on a bigger and more diverse dataset which will enhance both its accu- racy and its operational capabilities. Healthcare professionals will gain remote monitoring capabilities through the system's integration with cloud platforms and mobile applications. The system will use additional health parameters including oxygen saturation and body temperature to boost its prediction accu- racy. The system will achieve widespread hospital deployment and rural healthcare implementation through additional clinical trials and real-world field tests.

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