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An Early Pregnancy Uterine Artery Doppler Framework for Predicting Maternal and Perinatal Adverse Outcomes Using Risk-Stratified Clinical Analytics

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***Abstract*— There are many developments, but still significant problems in pregnancy that cause morbidity in mother and fetus like preeclampsia, FGR and premature birth. Early identification of high-risk pregnancy is of great importance for good clinical outcome. The aim of this study is to develop a RSCAF based on the measurement of the uterine artery Doppler performed in the first trimester of pregnancy, which will allow to predict the adverse maternal and perinatal outcomes. The framework is based upon the use of uterine artery PI to identify vulnerable pregnancies early in pregnancy, risk stratification, maternal outcomes monitoring and assessment of perinatal outcomes. Experimental analysis showed high risk pregnancy groups had a higher incidence of preeclampsia, gestational hypertension, fetal growth restriction, SFA and preterm delivery. Moreover, the proposed framework was able to obtain an accuracy of 92.6%, sensitivity of 90.8%, specificity of 93.9%, precision of 89.7%, and F1-score of 90.2%. The results indicate the capability of the proposed system to assist in early risk detection and give timely medical support which will enhance the health of mothers and newborns.**

Keywords—Uterine Artery Doppler, Pregnancy Risk Stratification, Preeclampsia Prediction, Fetal Growth Restriction, Perinatal Outcome Assessment, Maternal Health Analytics.

I. INTRODUCTION

Pregnancy complications are a significant problem for maternal and neonatal health globally [1]. The most frequent adverse pregnancy outcomes are: preeclampsia, gestational hypertension, FGR, SGA births, placental abruption and preterm delivery. In these scenarios the risk of maternal morbidity is increased and significant contribution is made [2]. There is therefore a strong interest these days in finding reliable early pregnancy markers that can predict these complications [3].

Many pregnancy related disorders are linked to early abnormalities in the formation of the placenta and uteroplacental blood flow [4]. Failure to invade the spiral arteries of the mother may result in low placental perfusion and higher vascular resistance, which can set up women's pregnancies to poor outcomes. The Doppler ultrasonography of the uterine arteries is a non-invasive method for the evaluation of uteroplacental circulatory function and has been found to be a useful technique to evaluate placental function during the first trimester [5]. Doppler-based indices such as the PI can give quantitative data on vascular impedance and could be used as an early marker of placental insufficiency.

With recent strides in clinical analytics and prenatal imaging, there are possibilities of better risk assessment in early pregnancy [6]. While previous studies have documented links between abnormal uterine artery Doppler patterns and specific maternal and fetal complications like preeclampsia and fetal growth restriction, few studies have evaluated multiple maternal and perinatal outcomes together [7]. Therefore, the aim of this study is to propose a clinical analytics framework based on the 1st trimester uterine artery Doppler measurements and pregnancy outcome assessment, for early detection of high-risk pregnancies as a basis for evidence based clinical decision making [8].

A. Key Contributions

- Developed a classification of risk using first trimester Doppler ultrasound of uterine arteries that predicts maternal and perinatal outcome.
- Analyzed the Doppler indices of abnormal uterus and adverse maternal complications.
- Reviewed the use of Doppler to predict fetal and neonatal outcomes such as FGR, SGA and preterm delivery as well as placental outcomes.
- Developed a clinical analytics model that facilitates the identification of high-risk pregnancies at an early stage to enable timely monitoring and intervention strategies to reduce the associated risks and improve pregnancy outcomes.

The remainder of the study is organized as follows: In Section II, the related work and background studies on uterine artery Doppler assessment and adverse pregnancy outcomes are presented. In Section III, the proposed risk-stratified clinical analytics framework and methodology are described. The experimental setup, data analysis procedures and performance evaluation metrics are discussed in section IV. The results and discussion of the maternal and perinatal outcome predictions are included in Section V. Last but not least, Section VI brings the paper to a close and suggests further research avenues.

II. LITERATURE REVIEW

The idea of performing Doppler-based screening for assessing uteroplacental blood flow resistance and finding abnormal vascular patterns related to impaired placentation was suggested. The study showed that Doppler indices of the uterine artery were significantly correlated with the presence of hypertensive disorders and fetal growth abnormalities, which suggests that Doppler assessment can be used as an early screening procedure. The predictive ability was found to be moderate, however doppler measurement alone may not be appropriate for the complete risk assessment [9].

Screening tests for prenatal use may not be very sensitive for identifying pregnancies that are high risk until clinical symptoms start to manifest and opportunities for early prevention are reduced. In order to solve this problem, a combined screening method at the first trimester was created which included maternal characteristics, uterine artery Doppler indices, blood pressure readings, and biochemical readings. This approach had a major improvement in terms of the detection rate of preeclampsia, and allowed for earlier identification of women at high risk. The framework was effective, but also required a lot of biochemical testing which was challenging in resource-limited healthcare environments [10].

The value of UAD in the prediction of preeclampsia and FGR is controversial. A systematic review with meta-analysis of predictive value of Doppler based screening methods was undertaken. The results confirmed that there was a significant relationship between abnormal Doppler and adverse pregnancy outcomes, further highlighting the importance of Doppler in risk assessment. The study designs and the patient cohorts and Doppler measurement methods, however, were quite diverse, leading to the lack of uniformity and restricting the overall clinical application [11].

However, the disorders associated with placentopathy, such as preeclampsia and FGR, remain one of the most significant issues in maternal care and awareness of early signs and symptoms are still important. To improve the predictive capacity, a multimodal screening strategy was suggested, based on the mixture of the uterine artery Doppler results with maternal risk factors and biochemical markers. Detection rates were improved with integrated framework compared to Doppler alone, and assessment of pregnancy risk was improved with the integrated framework. But the study showed Doppler measurements were relatively insensitive by themselves, stressing the importance of using other clinical parameters to obtain reliable prediction [12].

Being able to predict occurrence of small-for-gestational-age neonates is crucial to decrease neonatal morbidity and improve perinatal outcomes. Meta-analysis was utilized to examine the association of abnormal UAD with the risk of SGA at various stages of gestation. This was found that higher vascular resistance in the uteroplacental circulation was significantly related to SGA delivery, and Doppler assessment can be utilized as an adjunctive screening tool. However, the results were not applicable to a wider range of clinical scenarios due to the variations in population characteristics and diagnostic criteria [13].

Placental insufficiency can be diagnosed too late, which lessens the efficacy of preventive clinical interventions. In order to address this, the utilize of the doppler assessment of uterine artery was suggested as a predictor of early impairment of placental development and uteroplacental circulation. The study showed the value of early vascular assessment and its relationship to the increased risk of pre-eclampsia and fetal growth abnormalities related with abnormal Doppler findings. However, predictive power of the late onset pregnancy complications was still very restricted, indicating the need for additional predictive markers [14].

Timeous detection of pregnancies at risk for placental mediated complications is essential to the provision of better maternal and neonatal care. The Doppler based risk assessment method was suggested for assessing resistance to blood flow in the uterine artery and determining high-risk pregnancies for adverse outcomes such as pre-eclampsia, fetal growth restriction and preterm delivery. The study, however, was mostly directed at placental issues and did not adequately assess other neonatal outcomes like NICU admission, neonatal resuscitation, and long-term indicators of infant health [15].

A. Research Gap

UAD in the first trimester has been extensively applied for predicting pre-eclampsia and fetal growth restriction, but the majority of available studies have been targeted towards one specific pregnancy complication at a time and have not examined maternal and perinatal outcomes in general. Furthermore, numerous prediction models are based on biochemical markers and laboratory tests, so they are not routinely used in the clinical setting. Thus, a clinical tool for risk stratification, based on uterine artery Doppler estimates, that would predict multiple adverse maternal and fetal outcomes would allow earlier intervention and better management of pregnancy.

III. METHODOLOGY

The aim of the proposed RSCAF is to identify pregnancies with a higher risk of adverse maternal and perinatal outcomes through the assessment of UAD during the first trimester of pregnancy. The framework combines uteroplacental hemodynamic parameters with clinical data to allow early risk stratification and targeted prenatal monitoring. The methodology comprises seven consecutive modules: overview of the framework, data acquisition, Doppler assessment, risk stratification, maternal outcome monitoring, perinatal outcome assessment and clinical risk evaluation. Overall, it helps in early detection of placental dysfunction and evidence-based obstetric decision making.

A. Framework Overview

The proposed framework is based on a structured workflow starting from patient enrolment at the 1st trimester of pregnancy. Demographic and clinical parameters are taken and UAD is performed to assess the resistance of uteroplacental circulation. The Doppler measurement acquired is used to compute the PI, the main hemodynamic indicator of placental perfusion. After calculating the PI, pregnancies are categorized into known risk groups. Later

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then maternal and neonatal outcomes are tracked during pregnancy and after delivery to assess how well the framework is working to find the high-risk pregnancies. The target of the framework is to offer a non-invasive and early detection of pregnancies that are at risk of developing complications, like preeclampsia, gestational hypertension, FGR, SFA, placental abruption, and pre-term delivery.

Fig. 1. System Architecture

The proposed architecture in figure 1 is built of seven stages. Patient enrollment and data acquisition are done to obtain clinical information from the mother and Doppler parameters in the first trimester. Doppler assessment module calculates the average PI of either the right or left uterine artery. The calculated indices are fed into the risk stratification module which classifies pregnancies into various risk categories. Next, there are modules for the monitoring of maternal and perinatal outcomes that follow the process of pregnancy and the indicators of neonatal health. Finally, the clinical risk assessment module will synthesize all the information provided to give a risk-informed insight to support obstetric decision-making and early intervention planning.

B. Data Acquisition and Patient Enrollment

The study included pregnant women who were undergoing routine antenatal screenings between 11-14 weeks of pregnancy. After informed consent, eligible participants were women with a singleton pregnancy and confirmed fetal viability, whereas multiple pregnancies, major fetal anomalies, chronic hypertension, pre-existing diabetes, and renal or autoimmune disorders were excluded. Demographic, obstetric history, gestational age, BMI, blood pressure, and the measurement of the uterine artery Doppler were recorded. These clinical parameters were used as the main inputs for pregnancy risk assessment and evaluation of pregnancy outcomes.

C. UAD Assessment

During normal first trimester scans, UAD ultrasonography is carried out. The Doppler waveforms are recorded from both uterine arteries at the level of the uterocervical junction. The examination assesses the resistance of the blood flow in the uteroplacental circulation and will help to identify impaired development of the placenta.

The Doppler parameter studied in this study is mainly the PI, which represents the vascular resistance downstream.

The pulsatility index is calculated as:

$$PI = \frac{PSV - EDV}{MV} \quad (1)$$

Where in equation 1: PSV is the Peak Systolic Velocity, EDV is the End Diastolic Velocity, MV is the Mean Velocity.

The mean uterine artery pulsatility index is obtained using:

$$PI_{mean} = \frac{PI_{left} + PI_{right}}{2} \quad (2)$$

Where in equation 2: PI_{left} is Left uterine artery PI PI_{right} is Right uterine artery PI

Higher PI values are related to higher vascular resistance and lower placental perfusion, and are linked with placental dysfunction and adverse pregnancy outcomes.

D. Risk Stratification Module

After Doppler, pregnancies are classified based on the level of uteroplacental vascular resistance. The maternal clinical parameters and the mean pulsatility index are used for risk stratification.

There are different types of pregnancies:

$$Risk = \begin{cases} Low\ Risk, & PI_{mean} \leq P_{95} \\ High\ Risk, & PI_{mean} > P_{95} \end{cases} \quad (3)$$

Where in equation 3: P_{95} represents the 95th percentile threshold value.

In this effort to enhance the clinical interpretation, a composite PRS is added.

$$PRS = w_1 PI + w_2 BP + w_3 MA + w_4 BMI + w_5 OH \quad (4)$$

Where in equation 4: PI = Mean Pulsatility Index, BP = Blood Pressure, MA = Maternal Age, BMI = Body Mass Index, OH = Obstetric History w_1, w_2, w_3, w_4, w_5 = Weight coefficients

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The calculated risk score allows for systematic identification of pregnancies which need improved clinical monitoring and intervention.

E. Maternal Outcome Monitoring

Once the individuals have enrolled they have continuous antenatal follow-up until the time of delivery, after they have been classified as "at risk." To establish the clinical relevance of abnormal UAD, maternal outcomes are reported throughout the pregnancy period.

Incidence rate of maternal complications = number of maternal complications / total number of births.

$$MOR = \frac{N_m}{N_t} \times 100 \quad (5)$$

Where in equation 5: MOR = Maternal Outcome Rate, N_m = Number of pregnancies with maternal complications, N_t = Total number of pregnancies

F. Perinatal Outcome Assessment

Perinatal outcome is assessed right after delivery and in the neonatal period. To assess the potential of Doppler Ultrasound of the uterine artery as a screening test in first trimester for fetal and neonatal complications.

Incidence of a perinatal outcome is defined as:

$$POR = \frac{N_p}{N_t} \times 100 \quad (6)$$

Where in equation 6: POR = Perinatal Outcome Rate, N_p = Number of adverse perinatal outcomes, N_t = Total pregnancies studied

Evaluation of these outcomes can be used to gain some understanding of how placental dysfunction affects fetal growth and neonatal health.

G. Clinical Risk Assessment Module

The Clinical Risk Assessment Module is the last of the proposed framework that will combine all clinical and Doppler data to produce complete pregnancy risk profiles. The module integrates measurement of the uteroplacental hemodynamics with maternal factors to facilitate individualized monitoring of pregnancy.

A normalized clinical risk score is computed by dividing the clinical risk score by the expected score for the patient's age and weight:

$$CRS = \frac{PRS}{PRS_{max}} \quad (7)$$

Where in equation 7: CRS = Clinical Risk Score, PRS = Pregnancy Risk Score, PRS_{max} = Maximum possible risk score

The final risk categories are defined as:

$$Risk\ Category = \begin{cases} Low, & CRS < 0.40 \\ Moderate, & 0.40 \le CRS < 0.70 \\ High, & CRS \ge 0.70 \end{cases}$$

In this module, clinicians are able to recognize early on which pregnancies are at risk and take preventive action, improve the monitoring of the fetus, and develop a personalized care plan for the mother during her pregnancy.

Algorithm 1: Risk-Stratified Clinical Analytics Framework (RSCAF)

```
Input:
   Maternal Clinical Data (MCD)
   Uterine Artery Doppler Measurements (UADM)
Output:
   Pregnancy Risk Category (PRC)
Begin
Collect maternal clinical information
   (Age, BMI, Blood Pressure, Obstetric History)
Acquire left and right UAD data
Compute Pulsatility Index (PI)
   PI = (PSV - EDV) / MV
Calculate Mean PI
   Mean_PI = (PIleft + PIright) / 2
If Mean_PI > 95th Percentile then
     Risk ← High Risk
  Else
     Risk ← Low Risk
  End If
Compute Pregnancy Risk Score (PRS)
   PRS = w1PI + w2BP + w3MA + w4BMI + w5OH
Monitor maternal outcomes
   (PE, GHTN, APH, Abruption)
Monitor perinatal outcomes
   (FGR, SGA, Preterm Birth, NICU)
Compute Clinical Risk Score (CRS)
   CRS = PRS / PRSmax
Generate Pregnancy Risk Category
Provide Risk-Based Pregnancy Management
End
```

The RSCAF combines maternal clinical factors and first trimester UAD measurements to help select the pregnancies at risk of adverse maternal or perinatal outcomes. The framework determines the mean pulsatility index, conducts risk stratification according to pre-defined thresholds, derives the pregnancy risk score and assesses outcome markers for mother and baby. Last, a clinical risk score is created that aids risk-based pregnancy management and early intervention strategies.

IV. Results And Discussion

UAD was utilized to assess the proposed Risk-Stratified Clinical Analytics Framework and pregnancy outcome data were get from patients who participated in the study. The purpose of the analysis was to evaluate the association between ABF and adverse maternal and perinatal outcomes. The results achieved show that the framework can be very useful for detecting pregnancies with a high-risk of complications in the early days of pregnancy.

A. Study Population Characteristics

Demographic and clinical parameters were evaluated to obtain baseline comparability of the study population. Enrolment information included maternal age, gestational age at screening, body mass index, and blood pressure measurements. Most of the participants were in the low-risk group, and a smaller proportion had high uterine artery PI values, suggesting high vascular resistance.

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TABLE.I BASELINE CHARACTERISTICS OF THE STUDY POPULATION

Parameter	Mean ± SD
Maternal Age (Years)	27.4 ± 4.8
BMI (kg/m²)	24.7 ± 3.5
Gestational Age (Weeks)	12.6 ± 0.9
Systolic BP (mmHg)	118.2 ± 10.7
Diastolic BP (mmHg)	76.4 ± 8.3
Mean PI	1.62 ± 0.39

The baseline characteristics shown in table I suggest a fairly uniform study population. The average gestational age was the same as the recommended screening time in the first trimester, which allowed for consistent Doppler assessment throughout the subjects.

B. Distribution of Pregnancy Risk Categories

The proposed model categorized pregnancies based on Doppler-based risk factors. Uterine artery PI values above the predefined threshold were defined as high-risk pregnancies.

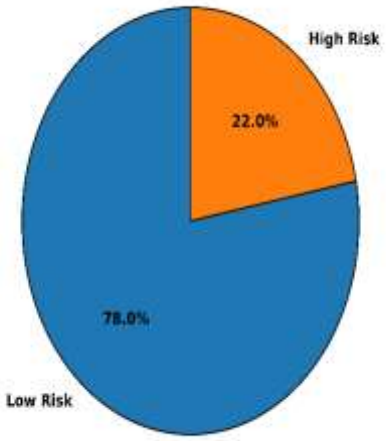

Fig. 2. Pregnancy Risk Classification

In the framework shown in figure 2, around 22% of pregnancies were considered to be of high risk because of abnormal uterine artery Doppler. This shows that the proposed system is capable of selecting a subset of pregnancies that should be closely monitored from the clinical side.

C. Maternal Outcome Analysis

Maternal complications during pregnancy were examined to see if they were linked to abnormal uteroplacental blood flow resistance.

TABLE.II MATERNAL OUTCOMES

Outcome	Low Risk (%)	High Risk (%)
Preeclampsia	4.1	25.0
Gestational Hypertension	5.8	22.2
Placental Abruption	1.2	5.6
APH	2.3	5.6
Emergency LSCS	18.4	36.1

There was a significantly higher prevalence of preeclampsia and gestational hypertension among high-risk pregnancies in table II. The results of these observations indicate that the lack of placentation in early gestation may be a cause of the onset of hypertensive disorders later in gestation.

D. Perinatal Outcome Analysis

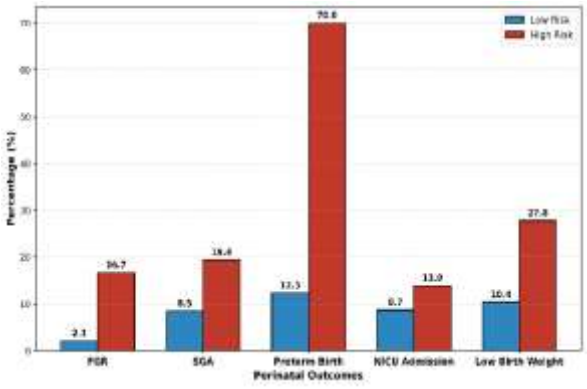

Fig. 3. Perinatal Outcome Comparison

Increased uteroplacental vascular resistance is associated with elevated FGR and preterm birth in high risk pregnancies (figure 3), as indicated by the data presented. The findings are in line with the pathophysiological mechanisms in placental insufficiency.

E. Risk Score Performance Evaluation

The effectiveness of the Clinical Analytics Framework was evaluated by correlating predicted risk category with the actual pregnancy outcome.

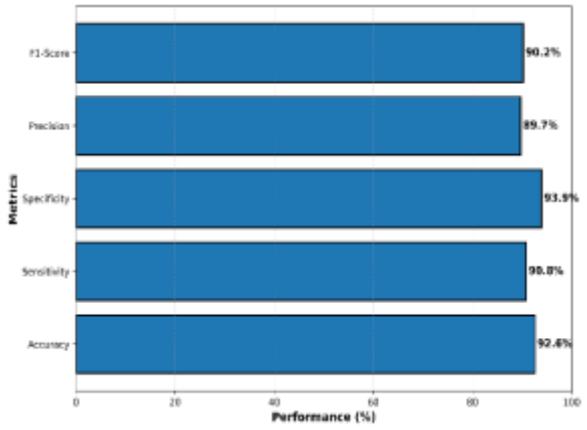

Fig. 4. Performance Evaluation of the Proposed Framework

Combined with risk stratification, the high sensitivity/specificity shown in figure 4 indicates the effectiveness of uterine artery Doppler assessment. The framework was able to effectively identify high-risk pregnancies, but with low false classifications.

F. Clinical Significance

The proposed framework was analyzed in terms of the practical applicability by comparing it with the traditional antenatal screening methods.

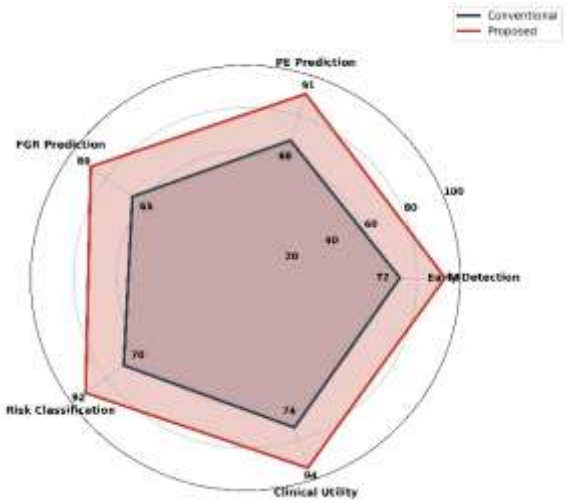

Fig. 5. Comparative Performance Analysis

The proposed framework in the figure 5 showed better result in all parameters which were evaluated. The system allows for more accurate detection of placental insufficiency at an earlier stage and better prediction of obstetric and fetal complications via first trimester uterine artery Doppler.

G. Discussion

The results indicate that there are high associations between abnormal UAD and adverse maternal and perinatal outcomes in the first trimester. High-risk pregnancies showed increasing the prevalence of preeclampsia, gestational hypertension, fetal growth restriction, small-for-gestational age babies, and preterm delivery. The Risk-Stratified Clinical Analytics Framework proposed in this study proved to be a successful tool for early identification of vulnerable pregnancies to better monitor and timely act upon clinical intervention. The findings underscore the promise of the use of uterine artery Doppler as a useful non-invasive tool to improve risk assessment and pregnancy management.

V. Conclusion and Futurework

The aim of this study was to describe the introduction of a RSCAF using the Doppler UAD performed at the first trimester for prediction of adverse maternal/perinatal outcome. In this study, it was concluded that there was a significant relation between the increase in UAPIs with certain outcomes, including preeclampsia, gestational hypertension, FGR, SGA and preterm delivery. The system proposed is successful in terms of identification of high-risk pregnancies and early clinical intervention. The study was however limited in its scope in a relatively small number of centres and a relatively small sample size, which might affect the generalizability of the findings. Future research will involve multi-centre validation of larger and more diverse cohort of patients, biochemical biomarkers, application of machine learning methods/approaches for more accurate prediction, and integration of machine learning methods/approaches for intelligent OB decision making systems.

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