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Original Research

The Value of a Combined Model of Biometric and Doppler Parameters in Predicting Adverse Pregnancy Outcomes in Late-Onset Fetal Growth Restriction

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Abstract

Background: Late-onset fetal growth restriction (FGR) is associated with an increased risk of adverse pregnancy outcomes (APOs). However, early identification of high-risk fetuses remains clinically challenging. This study aimed to evaluate clinical and Doppler ultrasound parameters as predictors of APOs and to develop a combined predictive model. **Methods:** A total of 91 cases of late-onset FGR were retrospectively evaluated. All fetuses underwent Doppler assessment of the umbilical artery (UA), middle cerebral artery (MCA), and ductus venosus (DV). Maternal and pregnancy characteristics, fetal biometry, and Doppler indices were analyzed for their associations with APOs. Receiver operating characteristic (ROC) curve analyses were performed to assess predictive performance, and a combined model was constructed incorporating significant clinical and Doppler variables. **Results:** APOs occurred in 65/91 (71.4%) cases. Maternal age was identified as an independent predictor (30.7 ± 4.5 vs. 28.1 ± 4.8 years; $p = 0.023$; odds ratio [OR]: 1.139, 95% confidence interval [CI]: 1.018–1.273). Gestational age (GA) at diagnosis, GA at delivery, abdominal circumference (AC), and estimated fetal weight (EFW) were also significantly associated with APOs ($p < 0.05$). Among Doppler parameters, only ductus venosus-pulsatility index for veins (DV-PIV) >95th percentile was significantly associated with APOs ($p = 0.023$; OR: 3.83; 95% CI: 1.78–10.99), whereas MCA pulsatility index (PI), UA-PI, and cerebroplacental ratio (CPR) showed no significant differences. ROC analyses indicated that individual variables demonstrated moderate predictive performance (area under the curve [AUC]: 0.613–0.663), with trade-offs between sensitivity and specificity. A combined model incorporating maternal age, gestational parameters, fetal biometry, and DV-PIV achieved superior predictive performance, with an optimal cutoff of 0.7625 (AUC: 0.747, 95% CI: 0.638–0.857), a sensitivity of 58.5% (95% CI: 0.464–0.704), and a specificity of 80.8% (95% CI: 0.656–0.959). **Conclusions:** In this cohort of late-onset FGR, DV Doppler findings above the 95th percentile and selected clinical parameters were associated with APOs. The combined model demonstrated moderate discriminative performance in identifying fetuses at higher risk of APOs; however, its predictive ability remains limited and requires further validation prior to clinical application. These findings suggest that integrated clinical and Doppler assessment may contribute to risk stratification in late-onset FGR.

Keywords: fetal growth restriction; adverse pregnancy outcomes; ductus venosus Doppler; fetal biometry; risk prediction model

1. Introduction

Fetal growth restriction (FGR), also referred to as intrauterine growth restriction (IUGR), is a pathological condition primarily caused by placental insufficiency and represents the second leading cause of neonatal mortality following preterm birth [1]. Notably, late-onset FGR, defined as occurring after 32 weeks of gestation, accounts for approximately 70–80% of all cases [2,3]. The 2016 Delphi consensus serves as the clinical standard for the diagnosis of FGR, emphasizing the importance of biometric parameters, such as abdominal circumference (AC) and estimated fetal weight (EFW), as well as vascular Doppler assessments, including the umbilical artery (UA), uterine artery, and middle cerebral artery (MCA) [4].

FGR is typically characterized by relatively milder placental lesions and subtler disturbances in oxygen and nutrient transfer. Currently, the diagnosis and monitoring of FGR rely primarily on Doppler assessment of the UA, MCA, ductus venosus (DV), and cardiotocography (CTG). More recently, several emerging parameters, such as the diastolic deceleration area of the fetal MCA and the cerebroplacental ratio (CPR), have been proposed to improve the prediction of perinatal outcomes in FGR pregnancies. This highlights the ongoing need for a comprehensive and reliable approach to the evaluation of FGR [5]. Doppler abnormalities in the UA and DV are predominantly observed in early-onset FGR. In contrast, the pulsatility index (PI) of the MCA and the CPR, defined as the ratio of MCA-PI to UA-PI, are considered the most relevant parameters for the

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assessment of late-onset FGR [6]. Consequently, current clinical guidelines for the monitoring and management of FGR increasingly recommend the combined use of multiple Doppler and fetal surveillance indices, rather than relying on any single parameter [7].

Abnormalities in UA Doppler values and specific alterations in the DV waveform—including absent or reversed a-wave or elevated PI—have been demonstrated across multiple studies to be associated with an increased risk of fetal compromise and acidemia [8]. Building on this evidence, the study by Yakout et al. (2021) [9] found that abnormal DV Doppler indices (e.g., PI, a-wave) were significantly more prevalent in fetuses with FGR and were strongly correlated with adverse neonatal outcomes.

Vietnam, a developing country in Southeast Asia, faces a high incidence of FGR, compounded by persistent challenges in diagnosis and management that contribute to a substantial burden on the national healthcare system. This study aimed to assess the predictive value of biometric and Doppler parameters for adverse perinatal outcomes in late-onset FGR and to develop a combined predictive model to improve prognostic accuracy and support clinical decision-making.

2. Methods

2.1 Study Design and Participants

This retrospective study was conducted from April 2023 to June 2024 at the Obstetrics and Gynecology Center of Hue Central Hospital, and Hue University of Medicine and Pharmacy Hospital, two institutions with prenatal screening and diagnostic centers officially recognized by the Vietnamese Ministry of Health. The study included women carrying singleton, viable, non-malformed fetuses diagnosed with late-onset FGR after 32 weeks of gestation. Gestational age (GA) was accurately determined for all participants based on first-trimester crown–rump length measurements obtained by ultrasound.

2.2 Sample Size

The sample size was estimated using the formula for calculating the sample size to estimate the population mean:

$$n = Z^2_{1-\alpha/2} \cdot \frac{\delta^2}{(\bar{X})^2 \cdot \varepsilon^2}$$

where n is the required sample size, $Z_{1-\alpha/2}$ is the standard normal deviate corresponding to a 95% confidence interval (CI) (1.96), where X is the expected mean value, and ε is the relative precision (relative error), and ε is the relative allowable error. Based on the study by Tran Thao Nguyen Nguyen [10], the standard deviation (δ) and mean value ($\bar{X}$) were 0.37 and 0.73, respectively. Assuming a relative error of approximately 10%, the minimum required sample size was calculated to be 99 participants. As this was a retrospective study, all eligible participants identified during the predefined study period were included in the analysis, resulting in a final sample of 91 participants.

Late-onset FGR was defined according to the Delphi consensus criteria, in the absence of congenital anomalies, as GA ≥32 weeks with AC/EFW < 3rd percentile, or with at least two of the following three criteria: (1) AC/EFW <10th percentile, (2) AC/EFW crossing >2 quartiles on growth charts, or (3) CPR <5th percentile or UA-PI >95th percentile [11].

EFW was calculated using the Hadlock IV formula [12]. Doppler ultrasound measurements were obtained in accordance with the guidelines of the International Society of Ultrasound in Obstetrics and Gynecology (ISUOG) [13]. To account for GA, EFW values were expressed as percentiles, and Doppler indices were standardized by conversion to multiples of the median (MoM) [14].

2.3 Research Steps

The research protocol began with a clinical examination to record baseline maternal and pregnancy characteristics. Participants subsequently underwent transabdominal ultrasound to assess fetal growth based on EFW. Ultrasound examinations were performed using a 5–7.5 MHz abdominal transducer on a Samsung WS80A ultrasound system by physicians with more than 10 years of experience who had been formally trained and certified in obstetric and gynecologic ultrasound in accordance with the regulations of the Vietnamese Ministry of Health.

Cases with an EFW below the 10th percentile underwent additional Doppler assessment, including evaluation of the UA, MCA, and DV. These Doppler parameters are well established for the assessment of fetal well-being:

$$\text{Pulsatility Index}(PI) = \frac{\text{Peak Systolic Velocity} - \text{End Diastolic Velocity}}{\text{Time} - \text{Averaged Maximum Velocity}}$$

$$\text{CPR} = \frac{\text{MCA-PI}}{\text{UA-PI}}$$

$$\text{Pulsatility index for veins}(PIV) = \frac{\text{Peak Systolic Velocity} - \text{Atrial Contraction Velocity}}{\text{Time} - \text{Averaged Maximum Velocity}}$$

Doppler parameters included the UA-PI, MCA-PI, CPR, and ductus venosus-pulsatility index for veins (DV-PIV). All measurements were performed in accordance with ISUOG standardized guidelines and recorded as continuous variables. UA-PI was considered abnormal when ≥95th percentile, while MCA-PI and CPR were considered abnormal below the 5th percentile. DV-PIV was measured during fetal quiescence with the sample volume placed at the inlet of the DV, and abnormal DV findings were defined

Table 1. Maternal characteristics and fetal anthropometry in late-onset FGR.

Parameter	No APOs (n = 26, %)	APOs (n = 65, %)	*p*-value
Maternal age (years), mean ± SD	28.1 ± 4.8	30.7 ± 4.5	0.023
BMI before pregnancy (kg/m^2), mean ± SD	19.9 ± 1.9	20.8 ± 3.0	0.288
Gravida			
Primigravida	14 (53.8)	26 (40.0)	0.232
Multigravida	12 (46.2)	39 (60.0)	
Previous FGR			
Yes	3 (11.5)	4 (6.2)	0.391
No	23 (88.5)	61 (93.8)	
Passive smoking	-	6 (8.2)	0.111
Hypertension, preeclampsia	6 (23.1)	15 (23.1)	0.273
GA at diagnosis (weeks)			
32–37	6 (23.1)	32 (49.2)	0.026
>37	20 (76.9)	33 (50.8)	
Mean ± SD	38.6 ± 1.3	37.2 ± 2.2	
GA at delivery (weeks)			
32–37	5 (19.2)	28 (43.1)	0.038
>37	21 (80.8)	37 (56.9)	
Mean ± SD	38.4 ± 1.1	37.5 ± 2.2	
Birth weight (g), mean ± SD	2246.2 ± 192.3	1963.8 ± 462.1	0.006
AC (mm), mean ± SD	288.8 ± 14.6	276.9 ± 25.8	0.035
EFW (g), mean ± SD	2175.4 ± 170.0	1979.1 ± 426.2	0.033

APOs, adverse pregnancy outcomes; BMI, Body mass index; SD, standard deviation; FGR, fetal growth restriction; GA, gestational age; AC, Abdominal Circumference; EFW, Estimated Fetal Weight.

as DV-PIV above the 95th percentile or absent/reversed a-wave [15]. In addition to Doppler surveillance, CTG was routinely used for fetal monitoring, alongside GA and overall fetal condition, informed clinical decision-making regarding the timing of delivery [16].

The diagnosis of late-onset FGR was established in accordance with the Delphi consensus and ISUOG guidelines. Pregnancies were subsequently followed continuously to monitor fetal health status. Management of late-onset FGR at our study institution was guided by International Federation of Gynecology and Obstetrics (FIGO) recommendations, considering GA, CTG monitoring, Doppler findings, and overall fetal condition [17]. The timing of delivery was individualized according to obstetric assessment and fetal surveillance results. Antenatal corticosteroids were administered when preterm delivery was anticipated, according to institutional protocols. Maternal and neonatal pregnancy outcomes were subsequently recorded. Adverse pregnancy outcomes (APOs) were defined considering the following criteria: emergency cesarean section due to fetal distress, Apgar score <7 at 1 minute, Apgar score <7 at 5 minutes, respiratory distress, need for respiratory support, and admission to the neonatal intensive care unit (NICU). Based on these data, associations were analyzed, a combined predictive model was developed, and the model's performance in predicting APOs was evaluated.

2.4 Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics version 20.0 (IBM Corp., Armonk, NY, USA). Data distribution was assessed using the Shapiro-Wilk test. Continuous variables with normal distribution are presented as mean ± standard deviation (SD), while non-normally distributed variables are presented as median (range). Categorical variables are expressed as frequency and percentage, n (%).

Categorical variables were compared using the chi-square test or Fisher's exact test, as appropriate. Continuous variables were compared using the independent-samples *t*-test for normally distributed data. Candidate variables for the multivariable logistic regression model were selected based on both clinical relevance and statistical significance in univariable analysis ($p < 0.05$). Logistic regression analysis was performed to identify independent predictors of APOs and to control for potential confounding factors.

To ensure clinical applicability, only variables available during antenatal assessment were included in the predictive model. For instance, EFW was used instead of birthweight, as birthweight is a postnatal variable unavailable at the time of antenatal decision-making. Receiver operating characteristic (ROC) curve analysis was performed to evaluate predictive performance. Optimal cutoff values for continuous variables were determined using the Youden index.

A two-sided p-value < 0.05 was considered statistically significant.

3. Results

Overall, 91 cases of late-onset FGR were diagnosed, of which 65 cases were associated with APOs. All cases underwent Doppler ultrasound evaluation of the UA, MCA, and DV.

Maternal and pregnancy characteristics are presented in Table 1 and Table 2. Maternal age was independently associated with APOs. Specifically, the mean maternal age was significantly higher in the APOs group compared with the control group (30.7 ± 4.5 vs. 28.1 ± 4.8 years, respectively; p = 0.023). In addition, GA at diagnosis, GA at delivery, EFW, and AC were each significantly associated with APOs (p < 0.05).

Table 2. Univariable logistic regression analysis of factors associated with APOs.

Variable	OR	95% CI	p-value
Maternal age	1.139	1.018–1.273	0.025
BMI before pregnancy	1.389	0.749–2.601	0.301
Gravida ≥2	1.750	0.697–4.393	0.232
Previous FGR	0.503	0.106–2.385	0.391
GA at diagnosis	3.232	1.151–9.089	0.026
GA at delivery	3.178	1.067–9.471	0.038
EFW	1.002	1.000–1.004	0.009
AC	1.028	1.002–1.055	0.036

CI, confidence interval; OR, odds ratio.

Abnormal DV Doppler indices were significantly associated with APOs, as shown in Table 3. Specifically, fetuses presenting with a DV-PIV above the 95th percentile had markedly higher odds of APOs compared with those with a normal DV-PIV (OR = 3.833; 95% CI: 1.784–10.992; p = 0.023). Although an absent or reversed DV a-wave was observed exclusively in the APOs group (3.1%), this difference was not statistically significant. In contrast, no significant differences were found between the two groups in MCA, UA, or CPR Doppler parameters; however, higher proportions of MCA-PI below the 5th percentile, UA-PI above the 95th percentile, and CPR below the 5th percentile were observed in the APOs group.

Based on area under the curve (AUC), sensitivity, and specificity analyses (Table 4 and Fig. 1), all evaluated variables demonstrated only moderate discriminatory ability for predicting APOs, with AUC values ranging from 0.613 to 0.663. Maternal age ≥29.5 years yielded the highest AUC (0.663; 95% CI: 0.530–0.795), with balanced sensitivity (66.2%) and specificity (65.4%), a relatively high positive predictive value (PPV: 82.7%), and a low negative predictive value (NPV 43.6%). GA at diagnosis ≤37 weeks yielded high sensitivity (92.3%) but very low specificity (11.5%), indicating limited usefulness as a standalone predictor despite an AUC of 0.642. GA at delivery ≤37 weeks, birth weight ≤1950 g, and AC ≤276.5 mm demonstrated high specificity (80.8%, 92.3%, and 84.6%, respectively) and high PPV, but relatively low sensitivity, suggesting these parameters perform better at confirming rather than excluding APOs. DV-PIV ≥0.525 demonstrated a comparable AUC (0.635; 95% CI: 0.509–0.749), with high sensitivity (86.2%) but low specificity (38.5%), indicating adequate detection capability but limited accuracy in excluding APOs. Overall, no individual parameter achieved strong predictive performance, supporting the need for combined models to improve diagnostic accuracy.

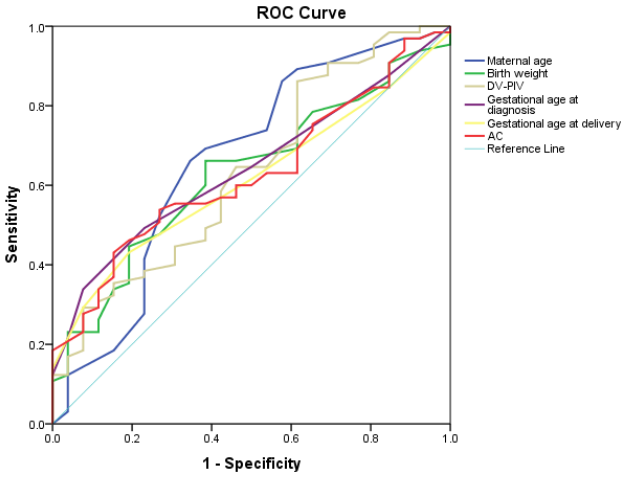

Fig. 1. Predictive value of clinical and vascular Doppler parameters for APOs.

Based on these findings (Fig. 2), a combined model was constructed, demonstrating improved predictive performance for APOs relative to individual variables. At a cutoff value of 0.7625, the model achieved an AUC of 0.747 (95% CI: 0.638–0.857), indicating good discriminative ability. Sensitivity was 58.5% (95% CI: 0.464–0.704) and specificity was 80.8% (95% CI: 0.656–0.959), reflecting good performance in identifying APOs cases. While the PPV was high (88.37%; 95% CI: 0.788–0.979), supporting the reliability of a positive test result, whereas the NPV remained modest (43.8%; 95% CI: 0.297–0.578). Overall, the combined model outperformed individual parameters, particularly in ruling in APOs, and may offer clinical utility in practice.

Y = –2.922 + 0.125 × Maternal age + 0.052 × EFW (per 100 g) + 2.044 × DV-PIV–0.024 × GA – 0.012 × AC

The predicted probability was calculated using the logistic regression equation:

$P = \frac{1}{(1+e^{-Y})}$

Cutoff: 0.7625

AUC = 0.747 (95% CI: 0.638–0.857)

Se = 58.5% (95% CI: 0.464–0.704)

Table 3. Doppler vascular characteristics in late-onset FGR.

Parameter	APOs (n = 65, %)	No APOs (n = 26, %)	*p*-value	OR (95% CI)
DV				
PIV >95th	47 (72.3)	23 (88.5)	0.023	3.833
PIV ≤95th	18 (27.7)	3 (11.5)		1.784–10.992
Reversed/Absent a-wave	2 (3.1)	-	0.999	
Normal	63 (96.9)	26 (100.0)		
MCA				
PI ≤5th	18 (27.7)	3 (11.5)	0.110	
PI >5th	47 (72.3)	23 (88.5)		
UA				
PI <95th	31(47.7)	15 (57.7)	0.390	
PI ≥95th	34 (52.3)	11 (42.3)		
CPR				
CPR ≤5th	26 (40.0)	8 (30.8)	0.412	
CPR >5th	39 (60.0)	18 (69.2)		

DV, ductus venosus; MCA, middle cerebral artery; UA, umbilical artery; PI, pulsatility index; PIV, pulsatility index of veins; CPR, cerebroplacental ratio.

Table 4. Predictive value of individual parameters for APOs in univariate analysis.

	Cutoff	AUC (95% CI)	Se (%) (95% CI)	Sp (%) (95% CI)	PPV (%) (95% CI)	NPV (%) (95% CI)
Maternal age (years)	29.5	0.663 (0.530–0.795)	66.2 (54.7–77.7)	65.4 (47.1–83.7)	82.7 (72.4–92.9)	43.6 (28.0–59.2)
GA at diagnosis (weeks)	37	0.642 (0.527–0.757)	92.3 (85.8–98.8)	11.5 (0–23.8)	72.3 (62.6–81.9)	37.5 (3.9–71.1)
GA at delivery (weeks)	37	0.613 (0.497–0.730)	43.1 (31.0–55.1)	80.8 (65.6–95.9)	84.9 (72.6–97.1)	36.2 (23.8–48.6)
Birth weight (g)	1950	0.630 (0.510–0.749)	44.6 (32.5–56.7)	92.3 (82.1–100.0)	93.6 (84.9–100.0)	40.0 (27.6–52.4)
AC (mm)	276.5	0.628 (0.511–0.746)	43.1 (31.0–55.2)	84.6 (70.8–98.4)	87.5 (76.1–98.9)	37.3 (25.0–49.6)
DV-PIV	0.525	0.635 (0.509–0.749)	86.2 (77.8–94.5)	38.5 (19.8–57.1)	77.8 (68.1–87.5)	52.6 (30.2–75.1)

AUC, area under the curve; Se, sensitivity; Sp, specificity; PPV, positive predictive value; NPV, negative predictive value.

Sp = 80.8% (95% CI: 0.656–0.959)

PPV = 88.4% (95% CI: 0.788–0.979)

NPV = 43.8% (95% CI: 0.297–0.578)

GA, Gestational Age; EFW, Estimated Fetal Weight; AC, Abdominal Circumference; PIV, Pulsatility Index for Veins; DV, Ductus Venosus; AUC, Area Under the Curve; Se, Sensitivity; Sp, Specificity; PPV, Positive Predictive Value; NPV, Negative Predictive Value.

4. Discussion

In this study, we evaluated clinical and Doppler ultrasound parameters associated with APOs in late-onset FGR. The overall incidence of APOs was relatively high (65/91, 71.4%), underscoring the significant clinical risk associated with this condition.

Maternal age was identified as an independent factor associated with APO, with risk increasing with advancing maternal age. This finding is consistent with previous reports suggesting that advanced maternal age may increase the risk of placental insufficiency and APOs, potentially through impaired placental vascular remodeling and altered maternal immune responses. These findings are consistent with the study by Powel et al. [18].

Pregnancy-related factors, including GA at diagnosis, GA at delivery, and fetal weight, were also significantly associated with APOs. Fetuses delivered at earlier GAs or with lower birth weights were at higher risk of APO, reflecting the pathophysiology of late-onset FGR, in which chronic placental underperfusion leads to fetal hypoxia and growth restriction [19]. Biometric parameters such as AC and EFW were similarly predictive, supporting their value as markers of fetal compromise.

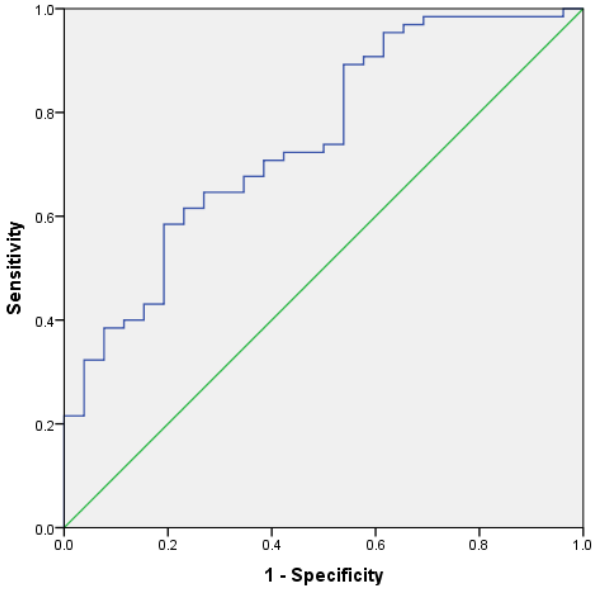

Fig. 2. Performance of the predictive model for adverse perinatal outcomes in late-onset FGR.

A multicenter study conducted in Sub-Saharan Africa defined APOs as small for GA, preterm birth, stillbirth, low birth weight, low Apgar score, and neonatal death within the first seven days of life. Associated factors included maternal age, antenatal care (ANC) attendance, educational level, maternal medical conditions, place of residence, distance to healthcare facilities, participation in decision-making, parity, hypertensive disorders during pregnancy, delayed referral, type of pregnancy, and obstetric emergencies [20].

Among Doppler indices, only DV measurements were significantly associated with APOs, particularly when DV-PIV exceeded the 95th percentile. This is consistent with the pathophysiology of fetal compromise, whereby chronic hypoxia increases central venous pressure and cardiac afterload, leading to alterations in DV flow as an early marker of fetal cardiovascular stress. In contrast, conventional Doppler parameters, including UA, MCA, and CPR, did not differ significantly between the APOs and control groups, although a trend toward a higher proportion of abnormal values was observed in the APOs group. These findings are consistent with prior studies showing that UA and MCA Doppler changes typically manifest only in severe or late-stage fetal compromise, limiting their predictive value for early detection of late-onset FGR. Morales-Roselló et al. suggested that DV-PIV elevation often represents the final stage in the hemodynamic progression of pregnancies complicated by early-onset FGR. It might be assumed that the parameter showing the latest hemodynamic deterioration would exhibit the strongest correlation with APOs [21]. In contrast, CPR has been considered a key determinant of APOs in late pregnancy, demonstrating superior predictive ability compared with DV-PIV [22].

ROC curve analysis revealed that individual variables demonstrated only moderate predictive performance. Maternal age ≥29.5 years, DV-PIV ≥0.525, and biometric parameters each exhibited either high sensitivity or high specificity, but not both, underscoring their individual limitations in predicting APOs. Consequently, a combined model incorporating clinical and Doppler factors was developed, which achieved an AUC of 0.747, a PPV of 88.4%, and a specificity of 80.8%, reflecting significantly improved predictive ability, particularly for identifying high-risk cases. However, the model's NPV remained modest, reflecting limitations in excluding APOs, which warrants careful consideration in clinical application.

Overall, this study highlights the importance of DV Doppler assessment and combined clinical-Doppler models in risk stratification for APOs in late-onset FGR. These findings are consistent with the underlying pathophysiology, whereby chronic fetal hypoxia leads to increased vascular resistance, cardiovascular stress, and altered DV flow preceding detectable abnormalities in UA, MCA, or CPR indices. The combined model provides a useful tool for risk assessment, enabling closer monitoring and timely intervention to improve perinatal outcomes.

Limitations

This study has several limitations. First, the relatively small sample size and single-center observational design may limit the generalizability and statistical stability of the predictive model. Although the number of outcome events was considered acceptable for multivariable analysis, the inclusion of multiple correlated predictors raises the risk of model overfitting. Furthermore, the sample size was calculated using a precision-based formula rather than methods specifically designed for prediction modeling studies. Future prospective studies should ideally determine sample size based on expected AUC, OR, or predictive model performance using dedicated statistical software. Second, several predictors included in the model, such as GA, AC, and birth weight, are biologically interrelated fetal growth parameters that may introduce multicollinearity. Although collinearity diagnostics did not reveal significant multicollinearity, the possibility of unstable parameter estimates cannot be entirely excluded. Third, the cutoff values were derived from the study dataset using ROC analysis and the Youden index, which may increase the risk of data-driven overfitting. Moreover, internal validation methods such as bootstrapping or cross-validation were not performed. Therefore, external validation in larger, multicenter prospective cohorts is required before clinical implementation. Finally, birth weight is determined only at delivery and may therefore have limited applicability in purely antenatal prediction settings. Accordingly, the current model should be interpreted primarily as an exploratory combined-risk model rather than a definitive antenatal clinical decision instrument.

5. Conclusions

In this cohort of late-onset FGR, abnormal DV Doppler findings and selected clinical parameters were associated with APOs. The combined model demonstrated moderate discriminative performance in identifying fetuses at higher risk of APOs; however, its predictive ability remains limited, and further validation is required before clinical implementation. These findings suggest that integrated clinical and Doppler assessment may contribute to improved risk stratification in late-onset FGR.

Availability of Data and Materials

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Author Contributions

DTT, MTL, VQHN, and TTNN conceptualized and designed the study. DTT, VDM, and MTT, TTNN were responsible for data collection and acquisition. VDM and DTT performed the statistical analyses and assisted in data interpretation. DTT, VDM, MTL and TTNN drafted the initial manuscript. All authors contributed to the interpretation of results, critically revised the manuscript for important intellectual content, and all authors read and approved the final manuscript. All authors agree to be accountable for all aspects of the work to ensure accuracy and integrity.

Ethics Approval and Consent to Participate

The study was approved by the Biomedical Research Ethics Committee of Hue University of Medicine and Pharmacy (Approval No. H2023/160), with institutional consent from Hue Central Hospital. All participants received complete study information, confidentiality was assured, and written informed consent was obtained from all participants prior to inclusion. The study was carried out in accordance with the guidelines of the Declaration of Helsinki.

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Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process

The authors declare that AI tools (ChatGPT-5.5, OpenAI) were used to assist in language editing, including spelling and grammar checking, and improving the clarity of the manuscript. All content was carefully reviewed and verified by the authors, who take full responsibility for the final version of the manuscript.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.31083/CEOG52514.

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