ORIGINAL ARTICLE *Van Medical Journal*

Van Med J 33 (1):104 -111, 2026
DOI: 10.5505/vmj.2026.17894

The Impact of Hemodynamic and Hematologic Markers on Postpartum Hemorrhage Risk in Hypertensive Pregnancies

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Abstract

Introduction: Postpartum hemorrhage (PPH) is a leading cause of maternal morbidity and mortality worldwide, particularly in hypertensive pregnancies. Identifying high-risk patients early is crucial for timely intervention. This study aims to develop and compare machine learning-based and conventional statistical models to predict PPH in hypertensive pregnancies using key clinical indicators, including hemoglobin levels, mean arterial pressure (MAP), and pulse rate.

Methods: This retrospective case-control study was conducted between 2016 and 2020 at a tertiary referral center in Turkey. A total of 64 pregnant women with hypertensive disorders of pregnancy (HDP) were included, with 32 developing PPH and 32 serving as controls. Logistic regression and random forest algorithms were used to assess the predictive significance of hemoglobin levels, MAP, and pulse rate. Hyperparameter tuning was performed using GridSearchCV with 5-fold cross-validation. Model performance was evaluated using sensitivity, specificity, F1-score, accuracy, and area under the receiver operating characteristic curve (AUC-ROC).

Results: Hemoglobin levels were significantly lower (9.7 g/dL vs. 11.9 g/dL, p=0.002), while MAP (103.0 mmHg vs. 96.7 mmHg) and pulse rate (90.0 bpm vs. 86.0 bpm) were significantly higher in the PPH group. Logistic regression demonstrated higher sensitivity (0.55 vs. 0.44) and positive predictive value (PPV) (0.83 vs. 0.80) compared to the random forest model. However, the random forest model had a lower shrinkage value (-0.001 vs. -0.116), suggesting better generalizability. A MAP ≥109.4 mmHg, pulse rate ≥97.6 bpm, and hemoglobin level <9.23 g/dL were associated with a 94% probability of developing PPH.

Conclusion: This study demonstrates that hemoglobin levels, MAP, and pulse rate can help identify hypertensive pregnant women at risk for PPH, emphasizing the need for early risk stratification to improve maternal outcomes.

Key words: Postpartum hemorrhage; hypertensive disorders of pregnancy; mean arterial pressure; hemoglobin; pulse rate; machine learning; logistic regression; random forest

Introduction

Postpartum hemorrhage (PPH) remains a leading cause of maternal morbidity and mortality worldwide, particularly in low- and middle-income countries (25103301). However, even in developed countries, PPH is a major contributor to maternal deaths, underscoring the need for early identification and intervention. PPH is typically defined as excessive blood loss of ≥500 mL following vaginal delivery or ≥1000 mL after cesarean section within the first 24 hours postpartum (1–3). PPH is a critical obstetric emergency that requires rapid recognition and management to prevent life - threatening complications. The early identification of patients at risk for PPH is crucial in guiding clinical decisions and improving maternal outcomes. Prolonged labor, multiple pregnancies, polyhydramnios, macrosomia, obesity, intrapartum pyrexia, uterine inversion, placenta percreta, placental abruption, and extra-genital bleeding are among the causes of postpartum hemorrhage (2,4,5). Another well-defined etiological factor is hypertensive disorders of pregnancy (HDP) (3).

The diagnosis of PPH is established through ultrasonography, blood pressure measurement, vital signs assessment, physical examination, and

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Received: 06.07.2025, Accepted: 14.11.2025

surgical evaluation (6,7). Hypovolemia and its secondary effects, such as hypotension and tachycardia, serve as crucial early warning signs for clinicians. The shock index, obtained by dividing systolic blood pressure by pulse rate, plays a significant role in the practical diagnosis of PPH (8–10). However, in patients with HDP, the elevated blood pressure values limit the utility of this diagnostic tool in assessing postpartum hemorrhage. This study aims to develop machine learning and classical statistical models to predict postpartum hemorrhage (PPH) in hypertensive pregnancies. We used the logistic regression and random forest algorithms to test how well key clinical indicators like hemoglobin levels, mean arterial pressure (MAP), and pulse rate could predict which patients would be at risk for PPH. With this study, we aim to enhance the accuracy of PPH prediction and provide healthcare professionals with a valuable tool for early risk assessment.

Material and Methods

This retrospective case-control study was conducted between 2016 and 2020 at the Health Sciences University Ankara Etlik Zübeyde Hanım Gynecology Training and Research Hospital (Ankara, Turkey). The study protocol was approved by the Ethics Committee of our center (Protocol ID: 30/10/2024-11), and written informed consent was obtained from all participants. The study was conducted in accordance with the universal ethical standards of the Declaration of Helsinki. The study included 32 pregnant women with hypertensive disorders of pregnancy (HDP) who were diagnosed with postpartum hemorrhage (PPH) as the study group and 32 hypertensive pregnant women without postpartum hemorrhage as the control group. Pregnant women aged 18–45 years who delivered at our clinic, were diagnosed with preeclampsia during pregnancy, and/or had blood pressure values ≥140/90 mmHg at hospital admission and were diagnosed and managed for postpartum hemorrhage at our clinic were included in the study. People who had a placental abruption or uterine rupture, gestational diabetes, multiple pregnancies, fetuses with aneuploidy or fetal anomalies, diabetes mellitus, chronic kidney disease, or endocrine disorders like hypothyroidism, hyperthyroidism, or adrenal insufficiency were not allowed to participate. Postpartum hemorrhage (PPH) is defined as excessive blood loss occurring within the first 24 hours after delivery. The commonly accepted diagnostic criteria include ≥500 mL of blood loss following vaginal delivery or ≥1000 mL after cesarean section. Severe PPH is typically classified as blood loss of ≥1500–2000 mL. In addition to the estimated blood loss, a hematocrit drop of ≥10%, the need for blood transfusion, or signs of hemodynamic instability (such as tachycardia, hypotension, oliguria, or pallor) are also considered diagnostic indicators of PPH. Based on these criteria, patients diagnosed with postpartum hemorrhage were included in the study. Blood pressure values were recorded at hospital admission and included systolic blood pressure (SBP) and diastolic blood pressure (DBP). Mean Arterial Pressure (MAP) was calculated using the following standard formula: MAP = (SBP + 2 * DBP) / 3 This formula accounts for the fact that the diastolic phase of the cardiac cycle lasts approximately twice as long as the systolic phase, providing a better reflection of tissue perfusion. Demographic information, including age, BMI (kg/m²), parity, mode of delivery, birth weight, and gestational age at delivery, was obtained from the hospital records system.

Ethical Approval: The study protocol was approved by the Ethics Committee of Health Sciences University Ankara Etlik Zübeyde Hanım Gynecology Training and Research Hospital (Approval No: 30/10/2024-11). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Statistical Analysis: All statistical analyses were performed using SPSS version 29.0 (IBM Corp., Armonk, NY, USA) and Python version 3.12. Continuous variables were presented as median (interquartile range, IQR) or mean ± standard deviation (SD), and categorical variables as frequencies and percentages. The Shapiro–Wilk test was used to assess normality. Group comparisons were made using the Mann–Whitney U test for nonparametric data and the independent-samples t-test for normally distributed variables. The Chi-square or Fisher's exact test was applied for categorical variables. A p-value of <0.05 was considered statistically significant. A univariate logistic regression analysis was first performed to identify variables associated with postpartum hemorrhage (PPH). Variables with $p < 0.10$ were entered into the multivariate model, and results were expressed as adjusted odds ratios (aOR) with 95% confidence intervals (CI). Clinically relevant predictors including mean arterial pressure (MAP), hemoglobin, and pulse were included based on their physiological relevance to hemodynamic stability and bleeding risk. Systolic (SBP) and diastolic (DBP) blood pressures were excluded due to multicollinearity with MAP, which provides a more integrated indicator of circulatory load. This variable selection strategy was designed to improve model stability and minimize redundancy among highly correlated parameters. Additionally, generalized linear models (GLM) were applied to estimate the predicted probability of PPH across varying levels of MAP, hemoglobin, and pulse.

Table 1: Comparison of Demographic, Admission, and Labour Findings Between Hypertensive Disorder of Pregnancy (HDP) Patients With and Without Postpartum Hemorrhage (PPH).

	HDP with PPH (n:32)	HDP without PPH (n:32)	P Value
Demographics			
Maternal age in years, median (IQR)	29.5 (25.0, 35.0)	30.5 (27.8, 37.3)	0.289
Parity, median (IQR)	1.5 (1.0, 2.2)	2.0 (1.0, 3.0)	0.856
Nulliparity, n (%)	2 (6.3)	3 (9.4)	0.641
Maternal body mass index at booking in Kg/m2, median (IQR)	28.5 (25.0, 36.0)	32.0 (29.8, 34.1)	0.158
Smoking, n (%)	1 (3.1)	3 (9.4)	0.302
Fertility Treatment, n (%)	3 (9.4)	2 (6.3)	0.641
Findings on admission, median (IQR)			
Hemoglobin Level (g/dL)	9.7 (8.9, 11.9)	11.9 (11.0, 12.4)	0.002
Pulse (beats per minute)	90.0 (87.8, 96.0)	86.0 (82.0, 87.3)	0.006
Systolic BP (mmHg)	140.0 (125.0, 140.0)	130.0 (120.0, 130.0)	0.013
Diastolic BP (mmHg)	90.0 (80.0, 90.0)	80.0 (70.0, 90.0)	0.018
Mean Arterial Pressure	103.0 (100.0, 107.0)	96.7 (89.7, 103.0)	0.002
Labour Findings			
Mode of Delivery, n (%)			0.320
SVD	4 (12.5)	7 (21.9)	
C-Section	28 (87.5)	25 (78.1)	
Gestationel age at birth in weeks, median (IQR)	37.0 (33.0, 37.3)	37.0 (36.0, 38.0)	*0.047*
Birth weight (gr), median (IQR)	3110 (2358, 3288)	3015 (2686, 3284)	0.945

HDP: Hypertensive disorder of pregnancy, PPH: Postpartum haemorrhage, IQR: Interquartile range, BP: Blood pressure, SVD: Spontaneous vaginal delivery

For machine learning-based prediction, both logistic regression and random forest (RF) algorithms were employed. Data preprocessing included z-score standardization (StandardScaler) and stratified train–test splitting (70/30%) to maintain class balance. Hyperparameter tuning was performed using GridSearchCV with 5-fold cross-validation to optimize model performance. Logistic regression used L2 regularization to prevent overfitting, while the RF model was tuned for the number of estimators (100–300), maximum depth (4–8), and minimum leaf size (3–10). Model performance was assessed using sensitivity, specificity, F1-score, accuracy, and the area under the ROC curve (AUC-ROC). To ensure robustness, bootstrap resampling (1,000 iterations) was used to calculate 95% CIs for AUC. Shrinkage, defined as the relative difference between training and test AUC ((Train AUC – Test AUC) / Train AUC), was calculated to assess model overfitting, with smaller values indicating higher generalizability. Feature importance in the RF model was derived using the mean decrease in impurity (Gini importance), and a representative decision tree was visualized to illustrate how key predictors contributed to PPH classification.

Results

The study included 64 pregnant women with hypertensive disorders of pregnancy (HDP), of whom 32 (50.0%) experienced postpartum hemorrhage (PPH). Table 1 presents the demographic, admission, and labor findings for both groups. The median maternal age and parity were comparable between groups (p=0.289 and p=0.856, respectively). There were no significant differences in smoking status, fertility treatment, or maternal body mass index at booking between the two groups (p>0.05).

Table 2: Univariate and Multivariate Logistic Regression Analysis of Predictors for Postpartum Hemorrhage in Patients with Hypertensive Disorders of Pregnancy.

	Univariate LR		**Multivariate LR**	
Predictor	OR (95% CI)	P Value	aOR (95% CI)	P Value
Hemoglobin Level	0.613 (0.440 – 0.854)	0.004	0.596 (0.394 -0.902)	0.014
MAP	1.110 (1.030 – 1.193	0.006	1.093 (1.004 - 1.189)	0.040
Pulse	1.090 (1.020 - 1.178)	0.019	1.118 (1.006 - 1.242)	0.038
Systolic BP	1.070 (1.020 – 1.118)	0.008		
Diastolic BP	1.076 (1.010 – 1.146)	0.020		

p<0.05 was considered statistically significant. LR: Logistic Regression, CI: Confidance Interval, OR: Odds Ratio, aOR: Adjusted OR, MAP: Mean Arterial Pressure, BP: Blood Pressure

Upon admission, hemoglobin levels were significantly lower in the HDP with PPH group compared to those without PPH (9.7 g/dL vs. 11.9 g/dL, p=0.002). Likewise, mean arterial pressure (MAP) was significantly higher in the PPH group (103.0 mmHg vs. 96.7 mmHg, p=0.002). Women with PPH also had significantly higher systolic (140.0 mmHg vs. 130.0 mmHg, p=0.013) and diastolic (90.0 mmHg vs. 80.0 mmHg, p=0.018) blood pressures at admission. Furthermore, pulse rate was significantly elevated in the PPH group compared to the non-PPH group (90.0 bpm vs. 86.0 bpm, p=0.006). The results of univariate and multivariate logistic regression analyses are summarized in Table 2. In univariate analysis, lower hemoglobin levels were associated with increased odds of PPH (OR: 0.613, 95% CI: 0.440–0.854, p=0.004). Higher MAP (OR: 1.110, 95% CI: 1.030–1.193, p=0.006) and increased pulse rate (OR: 1.090, 95% CI: 1.020–1.178, p=0.019) were also significant predictors of PPH. After adjusting for potential confounders in multivariate analysis, hemoglobin level remained a significant independent predictor of PPH (aOR: 0.596, 95% CI: 0.394–0.902, p=0.014). MAP (aOR: 1.093, 95% CI: 1.004–1.189, p=0.040) and pulse rate (aOR: 1.118, 95% CI: 1.006–1.242, p=0.038) also retained their significance as independent risk factors. Table 3 presents probability estimates for PPH based on different levels of pulse rate, MAP, and hemoglobin levels. Higher pulse rate and MAP values were associated with increased probabilities of developing PPH, while lower hemoglobin levels were correlated with higher PPH risk. The probability of PPH was highest among women with the lowest hemoglobin levels and highest MAP and pulse values. The predictive performance of machine learning-based and conventional statistical models for PPH is shown in Table 4. Logistic regression demonstrated higher sensitivity (0.55 vs. 0.44) and positive predictive value (PPV) (0.83 vs. 0.80) compared to the random forest model. Both models exhibited the same overall area under the curve (AUC = 0.925). The AUC 95% confidence interval was slightly wider for logistic regression (0.766 - 1.000) compared to random forest (0.738 - 1.000). Model shrinkage was notably greater in logistic regression (-0.116) than in the random forest model (-0.001), suggesting better generalizability for the latter. Figure 1 illustrates the classification tree developed using the random forest model, which identifies hemoglobin, MAP, and pulse rate as key predictors of PPH. The decision tree structure provides a visual representation of how these parameters interact to stratify risk levels.

Discussion

Our study demonstrates that postpartum hemorrhage (PPH) can be predicted in hypertensive pregnancies by evaluating hemoglobin levels, mean arterial pressure (MAP), and pulse rate. In hypertensive pregnant patients, hemoglobin levels below 9.23 g/dL, MAP above 109.4 mmHg, and pulse rate exceeding 97.6 bpm were associated with a 94% risk of developing PPH. These findings suggest that vital signs and hematological parameters could play a crucial role in early risk stratification, particularly in hypertensive pregnancies. Predicting PPH risk before the onset of classic signs such as hypovolemic shock or significant vaginal bleeding allows for timely intervention, ensuring that the surgical team is prepared and blood products are readily available for emergency transfusion. Early risk identification may be critical in reducing maternal morbidity and mortality. Although the shock index (SI) is widely used for hemorrhagic risk assessment, it may not always be reliable in obstetric patients. Le Bas et al. suggested that an obstetric shock index (OSI) between 0.7 and 0.9 is considered normal, whereas an OSI ≥1 is useful in predicting massive PPH and transfusion requirements (11). Similarly, Nathan et al. reported that an SI ≥1.7 indicates the need for urgent intervention, while SI <0.9 is reassuring (12). However, a systematic review by Makino et al. found that the predictive performance of the shock index for severe PPH was inconsistent, making its clinical utility uncertain. The study concluded that in high-income countries, there is insufficient evidence to support the use of the shock index alone as a screening tool for severe PPH, highlighting the need for well-designed studies (13). In this context, our study suggests

Table 3: Probability Estimates for Postpartum Hemorrhage Based on Different Levels of Pulse, Mean Arterial Pressure (MAP), and Hemoglobin Level.

							95% Confidence Interval	
Pulse		**MAP**	**Hemoglobin level**		**Probability**	**SE**	**Lower**	**Upper**
81.1	−	90.4 −	9.23	−	0.3482	0.1681	0.1112	0.695
			11.01	μ	0.1751	0.0914	0.0579	0.423
			12.80	+	0.0778	0.0525	0.0197	0.261
		99.9 μ	9.23	−	0.5532	0.1564	0.2638	0.811
			11.01	μ	0.3299	0.1100	0.1565	0.566
			12.80	+	0.1637	0.0842	0.0553	0.395
		109.4 +	9.23	−	0.7417	0.1468	0.3901	0.928
			11.01	μ	0.5330	0.1633	0.2398	0.805
			12.80	+	0.3121	0.1603	0.0950	0.662
89.3	μ	90.4 −	9.23	−	0.5727	0.1542	0.2805	0.822
			11.01	μ	0.3476	0.1116	0.1687	0.583
			12.80	+	0.1748	0.0879	0.0603	0.411
		99.9 μ	9.23	−	0.7565	0.0966	0.5265	0.897
			11.01	μ	0.5526	0.0844	0.3874	0.707
			12.80	+	0.3293	0.1086	0.1578	0.563
		109.4 +	9.23	−	0.8781	0.0748	0.6469	0.966
			11.01	μ	0.7412	0.1095	0.4833	0.898
			12.80	+	0.5324	0.1664	0.2349	0.808
97.6	+	90.4 −	9.23	−	0.7708	0.1411	0.4127	0.941
			11.01	μ	0.5721	0.1692	0.2565	0.838
			12.80	+	0.3470	0.1756	0.1042	0.708
		99.9 μ	9.23	−	0.8863	0.0742	0.6479	0.971
			11.01	μ	0.7561	0.1135	0.4813	0.912
			12.80	+	0.5520	0.1745	0.2361	0.831
		109.4 +	9.23	−	0.9476	0.0439	0.7615	0.990
			11.01	μ	0.8778	0.0840	0.6073	0.971
			12.80	+	0.7407	0.1641	0.3488	0.938

Note. − mean - 1SD, μ mean, + mean + 1SD MAP: Mean Arterial Pressure, SE: Standard Error that MAP and pulse rate could serve as more reliable alternatives, particularly in hypertensive pregnancies where hemodynamic parameters are altered. The mechanism of PPH in hypertensive pregnancies is more complex compared to normotensive pregnancies. Preeclampsia and other

Table 4: Comparison of Logistic Regression and Random Forest Models in Predicting Postpartum Hemorrhage in Patients with Hypertensive Disorders of Pregnancy

Metric	Logistic Regression	Random Forest
Sensitivity	0.55	0.44
Specificity	0.88	0.88
PPV	0.83	0.80
NPV	0.66	0.61
F1 Score	0.66	0.57
Accuracy	0.72	0.66
AUC	0,925	0.925
AUC 95% CI	0.766 - 1.000	0.738 - 1.000
Shrinkage	-0.116	-0.001

PPV: Positive predictive value, NPV: Negative predictive value, AUC: Area under curve, CI: Confidance intervale

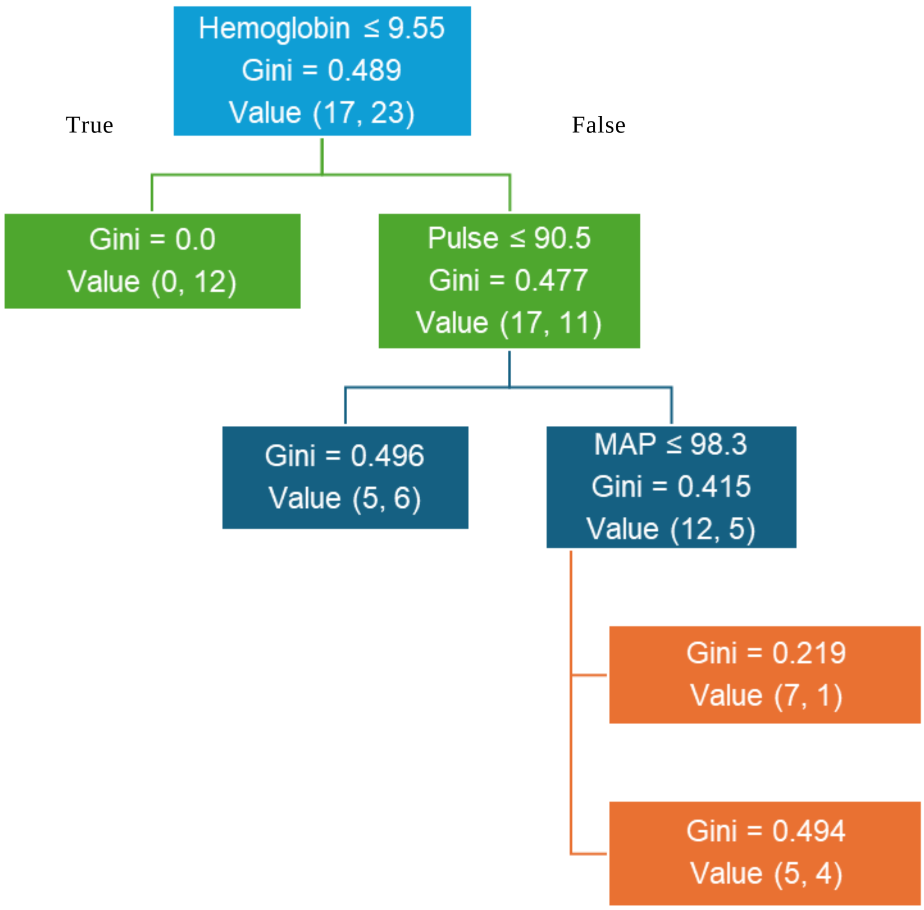

Figure 1: Decision Tree Representation for Predicting Postpartum Hemorrhage in Hypertensive Disorders of Pregnancy.

hypertensive disorders of pregnancy are associated with endothelial dysfunction, increased vascular resistance, and coagulation abnormalities. These conditions may impair uterine contractions and placental separation, increasing the risk of hemorrhage. While uterine atony is the most common cause of PPH in the general obstetric population, hemodynamic instability and vascular changes serve as additional risk factors in hypertensive pregnancies (14–18). Elevated MAP indicates increased systemic vascular resistance, leading to inadequate uteroplacental perfusion, weakened uterine contractility, and a higher risk of bleeding. The identification of MAP as a risk factor for PPH in our study underscores the importance of considering blood pressure dynamics in obstetric hemorrhage prediction. Another significant risk factor for PPH is anemia. A systematic review by Omotayo et al. demonstrated that severe prenatal anemia significantly increases the risk of PPH (OR = 3.54; 95% CI: 1.20–10.4, p = 0.020). These findings suggest that severe prenatal anemia is a strong predictor of adverse obstetric outcomes, warranting intensive management during pregnancy (19). In our study, anemia also emerged as an important risk factor for PPH. Machine learning (ML)-based models are promising tools for risk prediction in obstetric care. In our study, both logistic regression and random forest algorithms exhibited high predictive performance (AUC = 0.925). The logistic regression model showed higher sensitivity (0.55 vs. 0.44) and positive predictive value (PPV) (0.83 vs. 0.80), whereas the random forest model demonstrated better generalizability, as reflected by a lower shrinkage value (-0.001 vs. -0.116). The random forest model identified hemoglobin, MAP, and pulse rate as the most significant predictors, further emphasizing the clinical importance of these parameters. The decision tree model visually presents how these variables classify PPH risk, offering clinicians a valuable tool for identifying high-risk patients. The strengths of our study include the use of machine learning techniques to predict PPH risk in hypertensive pregnancies and the exclusion of major causes of hemorrhage, such as uterine rupture and placental abruption. However, this study has certain limitations. The relatively small sample size and single-center, retrospective design may limit the generalizability of the findings. Although the machine learning models demonstrated strong predictive performance, potential overfitting cannot be completely excluded. External validation in larger, multicenter cohorts is required to confirm their robustness and clinical applicability. Additionally, some variables were excluded to avoid temporal causality and multicollinearity, which may have led to the omission of subtle physiological associations. Future research should focus on larger, prospective studies incorporating additional clinical and biochemical parameters, such as coagulation markers and inflammatory mediators. Additionally, studies evaluating the impact of ML-based PPH prediction tools on clinical decision-making would be valuable.

Study Limitations: This study has several limitations. First, the relatively small sample size and single-center, retrospective design may limit the generalizability of the findings. Second, although machine learning models demonstrated high predictive performance, the risk of overfitting cannot be completely excluded despite the use of cross-validation and shrinkage analysis. Third, external validation in independent cohorts was not performed, which restricts the clinical applicability of the models. Finally, some potentially relevant clinical and biochemical variables were excluded to avoid multicollinearity and temporal bias. Larger, prospective, multicenter studies are needed to validate these findings.

Conclusion

In conclusion, our study demonstrates that PPH risk in hypertensive pregnancies can be effectively predicted using hemoglobin levels, MAP, and pulse rate. Machine learning models, particularly the random forest algorithm, may serve as valuable tools for understanding the complex interplay of hemodynamic and hematologic factors contributing to postpartum hemorrhage. Integrating these predictive models into clinical practice could facilitate early risk assessment and improve maternal outcomes. However, further large-scale studies are needed to validate these models for clinical implementation.

Ethical consent: Due to the retrospective design of the study, the requirement for written informed consent was waived by the Ethics Committee.

Conflict of interest: The authors declare no conflict of interest.

Financial support: This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Concept and design: V.Ö.A.

Data collection: V.Ö.A., C.O.U., A.K.

Statistical analysis: V.Ö.A.

Manuscript drafting: V.Ö.A.

Critical revision of the manuscript: All authors
Final approval of the manuscript: All authors

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