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A novel approach for the early prediction and prevention of placenta accreta spectrum and severe peripartum hemorrhage in patients with complete placenta previa: leveraging three-dimensional placental topography, cervical length, and dilatation parameters on magnetic resonance imaging

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Abstract

Background To evaluate the reliability of placental volume and other magnetic resonance imaging (MRI) markers for predicting placenta accreta spectrum and severe peripartum hemorrhage in patients with complete placenta previa.

Methods This single-center retrospective cohort study was conducted at a tertiary care facility and included 216 pregnant women diagnosed with complete placenta previa. Two radiologists, blinded to each other's assessments, independently evaluated the prenatal placental magnetic resonance imaging (pMRI) findings of 150 singleton pregnancies that met the inclusion criteria and were delivered in the third trimester. The three-dimensional placental volume (from the S1 and S2 sectors), cervical canal length (CCL), and degree of cervical canal dilatation (CCD) were compared with clinical and pathological findings. Univariate and multivariate logistic regression analyses identified risk factors for placenta accreta spectrum (PAS) and severe peripartum hemorrhage (SPPH). Receiver operating characteristic (ROC) curve analysis determined the cutoff values of significant predictors.

Results Univariate analysis revealed significant risk factors for PAS, including decreased cervical canal length (odds ratio [OR] = 1.330, $p < 0.001$), increased cervical canal dilation (OR = 1.869, $p < 0.001$), decreased S1 volume (OR = 1.008, $p < 0.001$), and increased S2 volume (OR = 1.008, $p < 0.001$). Multivariate analysis confirmed that cervical canal length was an independent risk factor (odds ratio [OR] = 1.253, $p = 0.03$). Significant predictors of severe peripartum hemorrhage included decreased cervical canal length (odds ratio [OR] = 0.406, $p = 0.006$), increased cervical canal dilatation (OR = 3.22, $p < 0.001$), decreased S1 volume (OR = 1.079, $p = 0.017$), and increased S2 volume (OR = 1.032,

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$p < 0.001$), all of which were confirmed as independent risk factors. ROC analysis demonstrated high precision for MRI markers, with area under the curve values above 0.8 for critical predictors of PAS and severe peripartum hemorrhage, confirming their reliability (all $p < 0.001$).

Conclusion This study emphasizes the pivotal role of three-dimensional placental volume measurements in the S1 and S2 sectors, along with cervical canal length and dilation, in predicting PAS and severe peripartum hemorrhage in patients with complete placenta previa. Integrating these advanced MRI markers into prenatal care can enhance early detection, improve clinical decision-making, and ultimately improve maternal and fetal outcomes.

Keywords Placenta accreta spectrum, Placenta previa, Surgical hemorrhage, Magnetic resonance imaging, Cervical length measurement, Cervical dilatation

Introduction

Placenta previa (PP) is a pregnancy and childbirth complication in which the placenta partially or completely obstructs the cervix, posing significant risks to maternal and fetal health [1]. Among these risks, placenta accreta spectrum (PAS), a group of disorders marked by abnormal placental attachment and invasion into the uterine wall, stands out for its potential severity and complexity [2]. PAS disorders include placenta accreta, increta, and percreta, each presenting a unique challenge owing to the varying depths of placental invasion [2]. A history of cesarean section (C/S) is the predominant risk factor for PAS development [3]. The likelihood of PAS increases from 0.3% in first-time C/S patients to approximately 7% in individuals with five or more C/S [4]. PP significantly increases the risk of PAS, with the incidence increasing in conjunction with the number of C/S. The likelihood of PAS increases from 3% for the first C/S to 67% for the fifth or subsequent C/S [4]. Therefore, effective diagnostic and management strategies are urgently needed.

Diagnostic approaches, including placental magnetic resonance imaging (pMRI) and color Doppler ultrasonography (CD-USG), have been the subject of debate regarding their comparative efficacy and complementary value in PAS diagnosis. Although the Society of Abdominal Radiology (SAR) and the European Society of Urogenital Radiology (ESUR) have recommended pMRI markers for the diagnosis of PAS in joint guidelines, the usefulness of pMRI in enhancing the antenatal diagnosis and preoperative management of PAS remains controversial [3, 4]. Although the American College of Radiology (ACR) and International Federation of Gynecology and Obstetrics (FIGO) recognize the utility of pMRI [2, 5], especially in complex cases, the American College of Obstetricians and Gynecologists (ACOG) remains cautious about its definitive benefits over CD-USG alone [1]. The lack of clarity regarding the diagnostic methodology applied, particularly in advanced healthcare settings where both pMRI and CD-USG are frequently used together, demonstrates significant uncertainty in our understanding and use of both technologies for managing PAS and highlights the urgent need for improvement.

Severe peripartum hemorrhage (SPPH) and postpartum hemorrhage are the leading causes of peripartum total abdominal hysterectomy (pTAH) due to PAS, affecting approximately 64% of pregnant women [3]. In cases in which bleeding cannot be controlled during delivery, maternal mortality can increase by 7% [3]. The location of PAS invasion and the extent of myometrial defects are critical factors for predicting significant blood loss [5]. The prognosis of these patients often depends on the exact location and extent of placental invasion, with specific areas at greater risk of severe hemorrhage [5]. Despite the effectiveness of CD-USG in diagnosing PAS, the potential of three-dimensional (3D) pMRI for detailed surgical planning and morbidity prediction remains underexplored and controversial.

Recent studies have elucidated the relationship between shortened cervical canal length (CCL) and adverse outcomes in patients with complete placenta previa (cPP), suggesting that the CCL is a potential prognostic indicator of maternal and fetal health [6–8]. Short CCLs are frequently observed in patients with high intraoperative blood loss [7]. In these studies, the CCL was typically measured using CD-USG [6–8], with limited data available from pMRI studies. Although previous studies have evaluated the effects of the CCL on maternal morbidity in patients with cPP, the impact of cervical canal dilation (CCD) on maternal and neonatal morbidity has not been reported.

Through this investigation, we aimed to establish a robust, objective standard that can enhance current diagnostic and management strategies for PAS and SPPH. Our goal is to contribute to improved maternal and fetal outcomes, a mission that will inspire and motivate us.

Methods

Study design, setting, and participants

This retrospective cohort study was conducted at a tertiary hospital with the approval of the Ethics Review Board (Approval No. 1428, June 2, 2021) and in strict adherence to the principles of the Declaration of Helsinki. We examined the medical records of pregnant women who were diagnosed with cPP between January

2018 and January 2024. Patient data were sourced from the Hospital Management Information System (HoMIS) and Electronic Health Records (EHRs) to ensure confidentiality and integrity. Informed consent was obtained from the patients for all possible medical interventions during hospitalization and before surgery.

This study examined the results of a large cohort of 216 pregnant women diagnosed with cPP between January 2018 and January 2024. Our study included 150 pregnant women aged 17–to 42 years with a cPP diagnosis via CD-USG and pMRI at 27⁺–37⁺ weeks of gestation. pMRI was performed between 27⁺ and 37⁺ weeks of gestation, encompassing the third trimester. This gestational age range was selected to reflect clinical scenarios where patients with cPP might require preterm delivery due to obstetric complications. Recognizing the significant variation of PV, CCD, and CCL with gestational age, we focused our analysis on the third trimester of pregnancy. This stratification allowed for an accurate assessment of the associations between placental volume, CCD, CCL, and outcomes such as PAS and SPPH, ensuring that the results are representative across different stages of late pregnancy [9, 10]. The analysis focused on singleton pregnancies with centrally located placenta previa in which the placenta completely covered the uterine cervix and extended to the anterior and posterior walls of the uterus. The study also included pregnant individuals who had undergone previous uterine surgery, such as myomectomy, C/S, or operative hysteroscopy for infertility.

Sixty-six patients with inappropriate clinical, laboratory, or imaging data were excluded from this study. Patients with placenta previa marginalis, severe anemia with preoperative hemoglobin levels less than 9.0 g/dL, coagulation disorders, morbidly obese, multiple fetal pregnancies, or who delivered before 27⁺ weeks of gestation were excluded (Fig. 1).

In the present study, 103 of the 150 patients diagnosed with CPP were confirmed to have PAS, representing 68.7% of the total cohort.

Standards of reference

The gestational ages of the patients were calculated using the declared last menstrual period and crown-rump length (CRL, mm) measurements obtained from CD-USG results obtained in the first trimester [11]. Transvaginal and transabdominal 2D CD-USG assessments were conducted at 30⁺–32⁺ gestational weeks, with additional scans performed at 34⁺–36⁺ gestational weeks to reassess placental location [12]. Patients with complete placenta previa underwent initial screening by two perinatologists, each with 12 years of experience in their field, using color Doppler ultrasonography (CD-USG). The goal was to identify sonographic markers indicative of PAS, such as placental lacunae, abnormal uteroplacental interface, bladder wall interruption, exophytic masses, and bridging vessels [13, 14]. (Voluson® E8 Expert, GE Healthcare Austria GmbH & Co. OG. Wide-band convex ultralight-volume and microconvex endocavitary-volume probes). Based on the CD-USG findings, patients suspected of having PAS were referred to the radiology department to evaluate pMRI. The objective of pMRI in this context was not to validate the initial ultrasound findings but to deliver a comprehensive evaluation of the depth of placental invasion, thereby informing surgical strategy and preoperative risk assessment. This approach was aligned with the recommendations of the Society for Maternal-Fetal Medicine (SMFM), which supports using ultrasound for initial PAS screening and reserving MRI for more detailed assessment when necessary [14].

In this study, MRI-based markers were selected to evaluate the placenta accreta spectrum (PAS), guided by the Society of Abdominal Radiology (SAR) and European

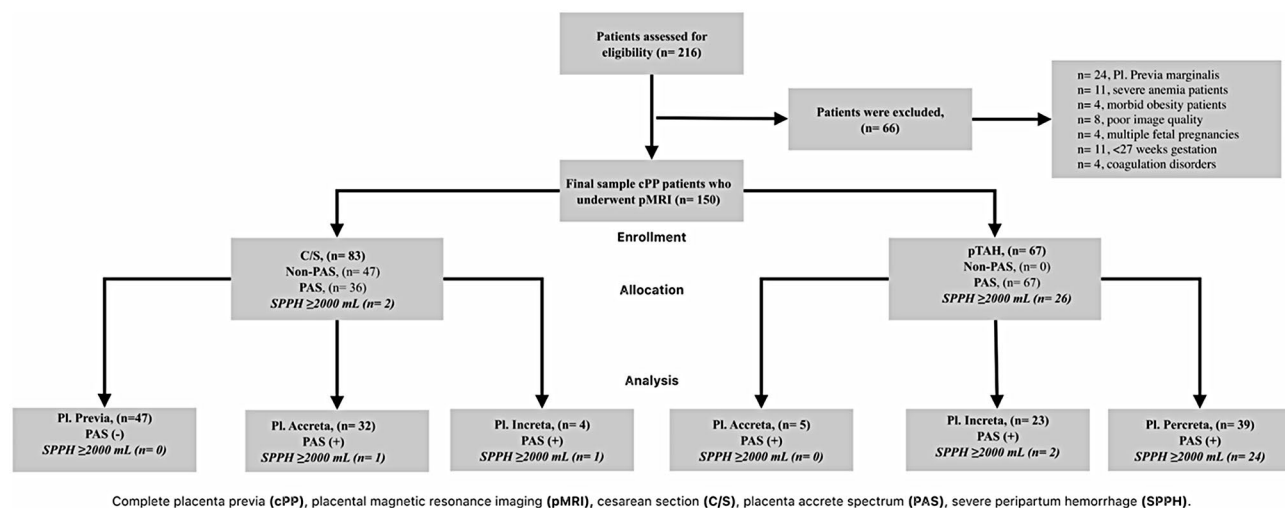


Fig. 1 Flowchart of patient selection for cPP

Society of Urogenital Radiology (ESUR) recommendations [3]. Focusing on high-sensitivity indicators such as intraplacental dark T2 bands, placental/uterine bulge, myometrial thinning, and bladder wall interruption for their detailed insights into the topography and depth of placental invasion was crucial for prenatal diagnosis and surgical planning [15]. Our emphasis on placental volume measurements in S1 and S2 provided a comprehensive volumetric assessment, enhancing the prediction of PAS and severe peripartum hemorrhage (SPPH), particularly in cases of complete placenta previa.

Two radiologists, each with at least 10 years of experience, evaluated the pMRI scans of pregnant women diagnosed with cPP. The radiologists were not provided with the original pMRI report. They independently evaluated the pMRIs for the study and were unaware of each other's assessments. Both radiologists confirmed the presence of PAS on pMRI under the guidelines of the International AIP Society (IS-AIP), SAR, and ESUR [3, 16]. Based on the anatomical categorization of PAS disorders proposed by Palacios Jaraquemada et al. [17], radiologists determined the boundaries of the placental invasion topography, which is closely related to surgical findings.

All participants in our study underwent C/S during the third trimester of pregnancy. Except for emergencies, all planned C/S and pTAH procedures were performed between 34⁺⁰ and 36⁺⁶ weeks. The same multidisciplinary team performed surgeries on all patients who gave birth because of suspected PAS [18]. The multidisciplinary team (MDT) comprised obstetricians, perinatologists, experienced radiologists, transfusion medicine specialists, obstetric anesthetists, pelvic surgeons, urologists, vascular surgeons, intensive care specialists, neonatologists, and expert placental pathologists [19]. (Please refer to Supplemental_Contents_1.docx and Supplemental_Contents_2.mov for further details on the standard surgical techniques and radiological guidelines employed in this study).

Clinical diagnosis and pathological reporting

To clinically diagnose PAS after laparotomy, the external surfaces of the uterus and pelvis were thoroughly examined for PAS. The preparation and approval of pathology reports followed a strict protocol that required the participation of two pathologists, each with at least 10 years of experience in their field. PAS disorders were identified via pathological examination and global morphological evaluation. Microscopic examination was based on biopsies obtained from the placental bed and uterus. Clinical and pathological classifications were determined according to criteria established by the FIGO Expert Consensus Panel on the Diagnosis and Management of Placenta Accreta Spectrum Disorders. The MDT followed the current FIGO guidelines for the conservative

and nonconservative surgical management of PAS based on the degree of accreta invasiveness [20] (Fig. 2).

MRI acquisition and interpretation

The study employed a 1.5T MRI system (Philips, Ingenia® 1.5T MR system, Netherlands) with body and spine array coils to perform pMRI scans in third-trimester pregnant women diagnosed with cPP. The imaging procedure was conducted in the supine position and lasted 15–20 min, with participants maintaining moderate urinary voiding to evaluate bladder invasion and prevent bladder distension complications. Various MRI sequences were optimized for image quality, including T2-weighted images in the sagittal, coronal, and axial orientations and T2-BTFE (balanced turbo field-echo) sequences. The repetition time (TR) and echo time (TE) were set at 2.9/100 ms for T2-weighted coronal images, 5.1/100 ms for T2-weighted axial images, and 3/2 ms for T2-BTFE sequences. T2-weighted sequences had a slice thickness of 5 mm, whereas T2-BTFE sequences had a slice thickness of 6 mm with a 90° flip angle. The reconstruction matrix was 256 for most sequences, 384 for T2-weighted axial and T2-BTFE sequences, and the field of view was 480×480 mm for T2-weighted sequences and 400×400 mm for T2-BTFE sequences. The comprehensive examination included the acquisition of 39 T2-weighted sagittal and 62 T2-BTFE axial sections, which yielded high-quality images of placental structure and function.

The pMRI results of all participants included in the study were assessed for cPP and PAS. The assessment focused on the position of the atypical placenta in the lower uterine segment, including the anterior, posterior, anterolateral, and posterolateral locations. Precise measurements were made for placental volume (PV, cm³) in the S1/S2 sector, cervical canal length (CCL, mm), and cervical canal dilatation (CCD, mm). CCD was measured using pMRI images in both sagittal and coronal planes. For cases where the cervix was not dilated, CCD was defined as the maximum diameter between the anterior and posterior walls of the cervical canal, measured at the level of the internal os. In cases where the cervix was dilated, CCD was recorded as the widest distance observed between the cervical walls along the longitudinal axis. This measurement technique allowed for consistent evaluation of CCD in patients with varying degrees of cervical dilation, ensuring uniformity in data collection and analysis (Fig. 3).

Segmentation of placental invasion (S1 and S2)

The placental invasion was categorized into two segments (S1 and S2) based on their anatomical relationship with the bladder, following the methodology of Palacios-Jaraquemada et al. [17, 21] and Familiari et al. [22]. S1

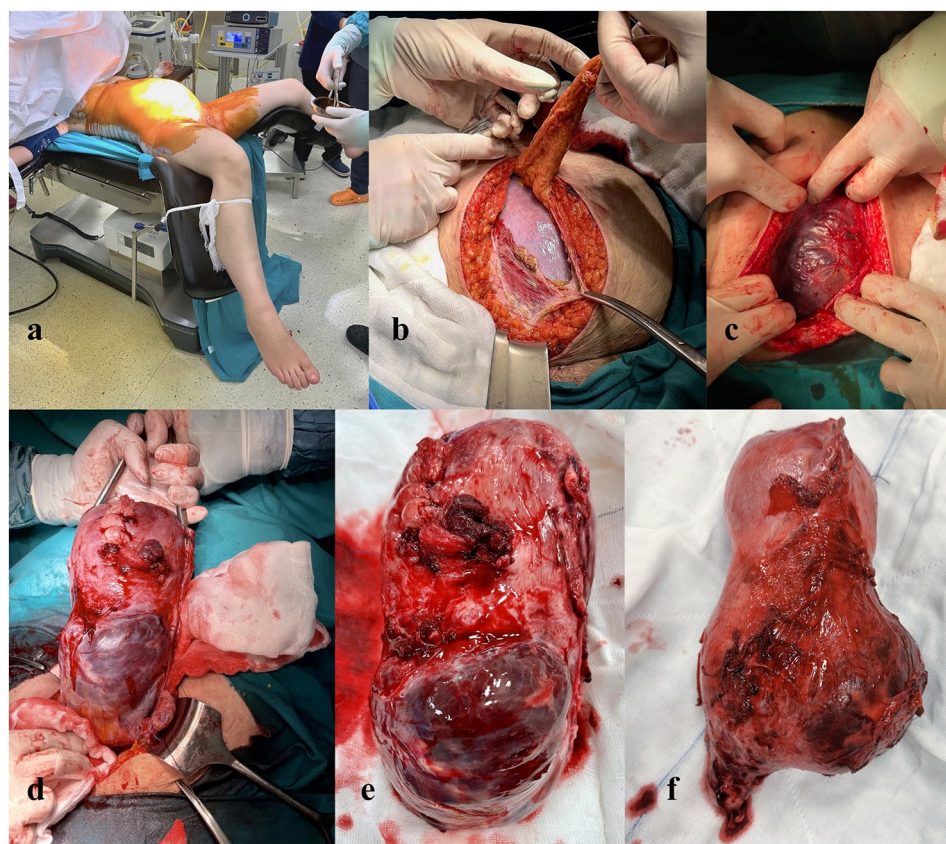


Fig. 2 Photographs depicting a 36-week pregnant woman undergoing pTAH because of cPP **a**) Dorsal lithotomy with a low Allen stirrup position; **b**) midline incision below the umbilicus; **c**) To detect placental invasion, surgeons carefully inspected the uterine serosal surface, lower uterine segment, bladder, parametrial tissues, and rectum during laparotomy; **d-e-f**) A trans-fundal vertical uterine incision was made to deliver the fetus, and the placenta was retained in the uterus following umbilical cord ligation

included the area adjacent to the upper posterior bladder wall, while S2 encompassed the lower uterine segment near the lower posterior bladder wall and cervix. This division was determined using a plane perpendicular to the superior-inferior axis of the bladder, derived from sagittal T2-weighted MRI images. The segmentation was performed using the Philips IntelliSpace Portal 12° workstation, which enabled a comprehensive 3D assessment of placental volume in each segment, aiding in surgical planning and risk stratification. Figure 3 presents pMRI images of a 34-week-pregnant woman with complete placenta previa (cPP) and placenta accreta spectrum (PAS). These images show the crucial uterine topography divided into S1 and S2 regions. The sagittal plane highlights the delineation between S1 (upper uterine segment) and S2 (lower uterine segment) based on their relationship with the posterior bladder wall, aiding in assessing placental invasion depth.

Estimation of blood loss

Intraoperative blood loss was quantified by summing the suction bottle contents and the weight difference (in grams) between the dry and soaked surgical sheets

and towels, assuming that 1 g equals 1 mL [23]. SPPH was defined as excessive blood loss of >2000 mL [21], a decreased hemoglobin level of 4 g/dL during the peripartum period, and the administration of at least four units of erythrocyte suspension [24]. Massive transfusion involves administering 10 units of packed erythrocyte suspension within 24 h or at least four units within 1 h for continuous blood loss [25]. In our hospital, the multidisciplinary team for massive transfusion performed a balanced transfusion strategy, which entails maintaining a 1:1:1 ratio of red blood cells (RBCs), platelets, and fresh frozen plasma (FFP) [25].

Power analysis and statistical methods

The sample width was computed using G*Power v3.1.9.6. A comparison of all pMRI values between patients with and without PAS in the reference trial revealed a substantial effect. Using 95% confidence (1- α), 95% test power (1- β), $d=0.8$ effect size, and a two-way hypothesis, the study aimed to enrol 84 patients, with a minimum of 42 patients per group. According to a post hoc analysis [26], the test had 99.8% power after 150 cases.

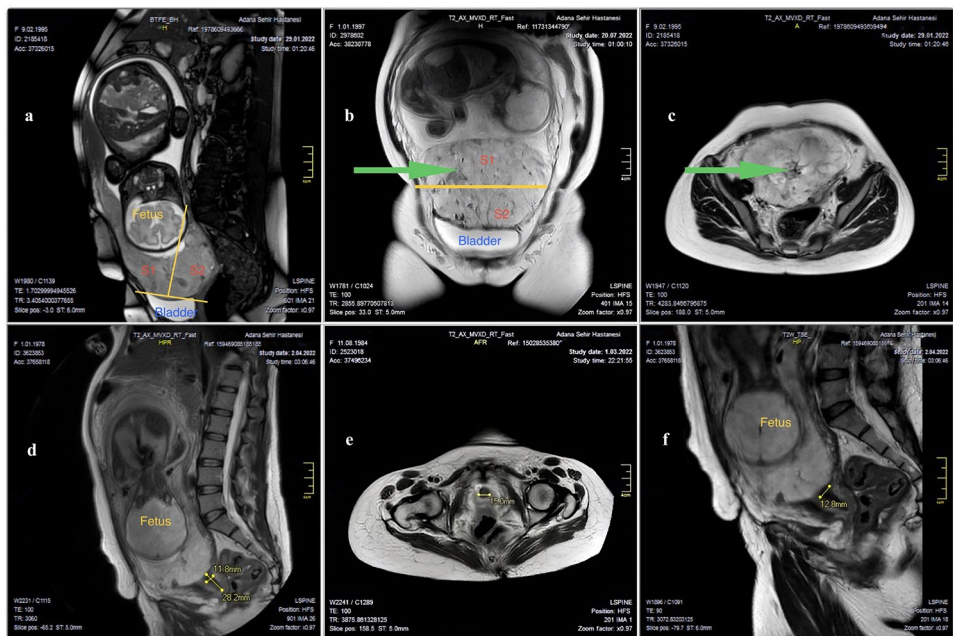


Fig. 3 Coronal, sagittal, and axial pMRI images of a 34-week pregnant woman with cPP and PAS. **a-b)** An illustration showing the topography of placental invasion. pMRI images in the sagittal and coronal planes were used to divide the topography into two parts (yellow lines). The area bordering the upper and back walls of the bladder is referred to as the upper uterine segment (S1), whereas the area adjacent to the lower and back walls is called the lower uterine segment (S2); **b-c)** The green arrow shows the dark intraplacental band and placental infarct areas; **d-e-f)** The small yellow lines show the CCL and CCD measurements

Descriptive statistics	Mean ± SD	Median (min.– max.)
Maternal age (years)	31.6 ± 5.7	32 (17–44)
Length of hospital stay	5.7 ± 3.3	5 (2–15)
Gravida	4.2 ± 1.9	4 (1–10)
D&C	0.5 ± 1.1	0 (0–6)
C/S	1.8 ± 1.6	2 (0–6)
NSVD	0.8 ± 1.5	0 (0–8)
fBW (g)	2378.0 ± 582.4	2420 (800–3750)
PPH (mL)	1480.7 ± 605.1	1350 (700–3800)
ES (units)	2.0 ± 1.8	2 (0–7)
FFP (units)	2.0 ± 1.8	2 (0–7)
PLTs (units)	1.7 ± 1.9	1.5 (0–7)
PFC (vials)	1.6 ± 1.8	0 (0–6)
CCL (mm)	35.8 ± 9.8	37 (11–54.6)
CCD (mm)	9.2 ± 4.4	9 (2.5–26)
S1 (cm3)	419.4 ± 220.1	443.9 (51.4–810.1)
S2 (cm3)	344.1 ± 215.0	329.3 (39.8–812.3)

Abbreviations Number of abortions/curettage (D&C), Number of cesarean births (C/S), Number of spontaneous vaginal delivery (NSVD), Fetal birth weight (grams) (fBW), Peripartum hemorrhage (PPH, mL), Used Red Blood Cell Suspensions (unit) (ES), Used Fresh Frozen Plasma (unit) (FFP), Utilized Platelet Suspension (unit) (PLTs), The amount of purified fibrinogen concentrate used (vial) (PFC)

Data analysis was performed using IBM SPSS V23. The Shapiro–Wilk and Kolmogorov–Smirnov tests were used to assess normality. Nonnormally distributed matched group data were compared using the Mann–Whitney U test. Group-based categorical variables were analyzed

with Pearson’s chi-square test, Yates correction, and Fisher’s exact test. Kruskal–Wallis H and Dunn tests were used to compare nonnormally distributed data among groups of three or more individuals. The cutoff values for surgical procedure variables were determined using receiver operating characteristic (ROC) analysis. Univariate and multivariate binary logistic regression analyses were used to examine independent surgical risk factors. The backward Wald test was used for multivariate binary logistic regression. The results are presented as the mean ± standard deviation, median (minimum–maximum), and frequency (percentage) for quantitative and categorical variables. Kappa tests and intraclass correlation coefficients were used to assess the reliability of the intra- and interobserver agreements. The significance level was set at $p < 0.05$.

Results

Tables 1 and 2 present the results of descriptive statistics and univariate and multivariate analyses of independent risk factors for PAS status. Univariate analysis provided a comprehensive view of PAS risk factors on pMRI, including decreased CCL values, increased CCD values, anterior placental localization, decreased placental volume in S1, increased volume in S2, and the presence of AVPB, PII, and HP. The multivariate model confirmed that the risk of PAS increased with decreasing CCL. However, other factors, such as CCD, S1, and S2, did not

Table 2 Examination of independent risk factors affecting PAS status by logistic regression analysis

pMRI	PAS (+/-)		Univariate		Multivariate	
	Non-PAS (n = 47)	PAS (n = 103)	OR (95% CI)	p value	OR (95% CI)	p value
CCL (mm)	44.76 ± 5.54	31.74 ± 8.53	0.752 (0.683 – 0.829)	< 0.001	0.798 (0.651 – 0.979)	0.03
CCD (mm)	5.61 ± 2.33	10.87 ± 4.17	1.869 (1.526 – 2.288)	< 0.001	1.154 (0.726 – 1.833)	0.545
Placental implantation						
Anterior	8 (19.5)	33 (80.5)	Reference			
Posterior	26 (40.6)	38 (59.4)	0.354 (0.141 – 0.889)	0.027	1.378 (0.255 – 7.46)	0.71
Anterolateral	2 (13.3)	13 (86.7)	1.576 (0.295 – 8.431)	0.595	1.646 (0.131 – 20.665)	0.699
Posterolateral	11 (36.7)	19 (63.3)	0.419 (0.143 – 1.223)	0.111	1.467 (0.217 – 9.911)	0.694
S1 (cm ³)	611.09 ± 162.98	331.92 ± 184.82	0.992 (0.989 – 0.995)	< 0.001	0.999 (0.992 – 1.006)	0.797
S2 (cm ³)	168.74 ± 149.75	424.08 ± 191.72	1.008 (1.005 – 1.011)	< 0.001	0.997 (0.99 – 1.004)	0.366
AVPB						
No	37 (75.5)	12 (24.5)	Reference			
Yes	10 (9.9)	91 (90.1)	28.058 (11.158 – 70.556)	< 0.001	5.136 (1.258 – 20.971)	0.023
PII						
No	46 (40.4)	68 (59.6)	Reference			
Yes	1 (2.8)	35 (97.2)	23.676 (3.132 – 178.959)	0.002	0.27 (0.019 – 3.848)	0.334
HP						
No	43 (65.2)	23 (34.8)	Reference			
Yes	4 (4.8)	80 (95.2)	37.391 (12.144 – 115.128)	< 0.001	8.038 (1.677 – 38.521)	0.009
FEM						
No	47 (43.9)	60 (56.1)	---	---	---	---
Yes	0 (0)	43 (100)	---	---	---	---
BWI						
No	47 (37.6)	78 (62.4)	---	---	---	---
Yes	0 (0)	25 (100)	---	---	---	---
MT						
No	47 (58.8)	33 (41.3)	---	---	---	---
Yes	0 (0)	70 (100)	---	---	---	---
LDPB						
No	42 (100)	0 (0)	---	---	---	---
Yes	5 (4.6)	103 (95.4)	---	---	---	---
DIB						
No	47 (52.2)	43 (47.8)	---	---	---	---
Yes	0 (0)	60 (100)	---	---	---	---
PB						
No	47 (40.5)	69 (59.5)	---	---	---	---
Yes	0 (0)	34 (100)	---	---	---	---

Abbreviations placental MRI (pMRI); odds ratio (OR); confidence interval (CI); uterine cervical canal length (CCL, mm); uterine cervical canal dilatation (CCD, mm); placental volume in the uterine upper segment (S1, cm³); placental volume in the uterine lower segment (S2, cm³); decreased signal intensity (T1W); areas of increased signal intensity (T2W); abnormal vascularization of the placental bed (AVPB, T2W); placental ischemic infarction (PII, T2W/T1W); heterogeneous placenta (HP, T2W/T1W); focal exophytic mass (FEM, T2W/T1W); bladder wall interruption (BWI, T2W); myometrial thinning (MT, T2W); loss of the thin dark lie beneath the placental bed (LDPB, T2W); dark intraplacental bands (DIB, T2W); placental bulge (PB, T2W/T1W) and mean ± standard deviation, frequency (percentage)

significantly affect the risk of PAS. As indicated in the model, the presence of an AVPB is a critical factor that increases the risk of PAS; however, the PII does not affect this risk. Furthermore, the model emphasized that HP significantly increased the incidence of PAS.

As shown in Table 3, ROC analysis was performed to determine the cutoff values of CCL (mm), CCD (mm), S1 (cm³), and S2 (cm³) for PAS status. S1 and S2 are essential determinants for the diagnosis of PAS. Although their sensitivity was lower than that of the CCL and CCD, their specificity and positive predictive value (PPV) were

significant, particularly for S2. S1 shows a valuable balance between sensitivity and specificity, making it a reliable predictor of high PPV. S2, in contrast, stands out for its exceptionally high specificity and PPV, making it effective in confirming the presence of PAS.

Table 4 shows the key predictors of SPPH (≥ 2000 mL) in patients with cPP. The significant factors included decreased CCL (OR = 0.406, $p = 0.006$), increased CCD (OR = 3.22, $p < 0.001$), reduced S1 volume (OR = 0.927, $p = 0.017$), and increased S2 volume (OR = 1.032, $p < 0.001$). Placental implantation in the posterior

Table 3 ROC analysis results of variables for PAS disorders

PAS	Cutoff	AUC (95% CI)	p value	SE	SP	PPV	NPV
CCL (mm)	≤ 39.0	0.913 (0.867–0.959)	< 0.001	90.3%	78.7%	90.3%	78.7%
CCD (mm)	≥ 8.0	0.89 (0.837–0.943)	< 0.001	88.4%	70.2%	86.7%	73.3%
S1 (cm ³)	≤ 491.5	0.865 (0.802–0.928)	< 0.001	83.5%	78.7%	89.6%	68.5%
S2 (cm ³)	≥ 344.2	0.839 (0.772–0.906)	< 0.001	64.1%	91.5%	94.3%	53.8%

Abbreviations uterine cervical canal length (CCL, mm), uterine cervical canal dilatation (CCD, mm), placental volume in the upper uterine segment (S1, cm³), placental volume in the lower uterine segment (S2, cm³), the area under the curve (AUC), positive predictive value (PPV), and negative predictive value (NPV)

Table 4 Logistic regression analysis of the independent risk factors affecting peripartum hemorrhage status

MRI	Severe peripartum hemorrhage (SPPH)		Univariate	p value
	< 2000 mL (n = 122)	≥ 2000 mL (n = 28)	OR (95% CI)	
CCL (mm)	39.36 ± 6.91	20.39 ± 3.42	0.406 (0.214–0.77)	0.006
CCD (mm)	7.68 ± 2.77	15.96 ± 3.97	3.22 (1.97–5.262)	< 0.001
Placental implantation				
Anterior	21 (51.2)	20 (48.8)	Reference	
Posterior	63 (98.4)	1 (1.6)	0.017 (0.002–0.132)	< 0.001
Anterolateral	10 (66.7)	5 (33.3)	0.525 (0.153–1.807)	0.307
Posterolateral	28 (93.3)	2 (6.7)	0.075 (0.016–0.357)	0.001
S1 (cm ³)	490.2 ± 178.92	110.88 ± 51.16	0.927 (0.87–0.987)	0.017
S2 (cm ³)	271.46 ± 164.66	660.44 ± 76.66	1.032 (1.018–1.047)	< 0.001
FEM				
No	102 (95.3)	5 (4.7)	Reference	
Yes	20 (46.5)	23 (53.5)	23.46 (7.972–69.039)	< 0.001
BWI				
No	117 (93.6)	8 (6.4)	Reference	
Yes	5 (20)	20 (80)	58.5 (17.378–196.931)	< 0.001
MT				
No	79 (98.8)	1 (1.3)	Reference	
Yes	43 (61.4)	27 (38.6)	49.605 (6.514–377.768)	< 0.001
PII				
No	108 (94.7)	6 (5.3)	Reference	
Yes	14 (38.9)	22 (61.1)	28.286 (9.794–81.69)	< 0.001
DIB				
No	89 (98.9)	1 (1.1)	Reference	
Yes	33 (55)	27 (45)	72.818 (9.511–557.508)	< 0.001
PB				
No	111 (95.7)	5 (4.3)	Reference	
Yes	11 (32.4)	23 (67.6)	46.418 (14.719–146.384)	< 0.001

Abbreviations placental MRI (pMRI); odds ratio (OR); confidence interval (CI); uterine cervical canal length (CCL, mm); uterine cervical canal dilatation (CCD, mm); placental volume in the uterine upper segment (S1, cm³); placental volume in the uterine lower segment (S2, cm³); decreased signal intensity (T1W); areas of increased signal intensity (T2W); abnormal vascularization of the placental bed (AVPB, T2W); placental ischemic infarction (PII, T2W/T1W); heterogeneous placenta (HP, T2W/T1W); focal exophytic mass (FEM, T2W/T1W); bladder wall interruption (BWI, T2W); myometrial thinning (MT, T2W); loss of the thin dark lie beneath the placental bed (LDPB, T2W); dark intraplacental bands (DIB, T2W); placental bulge (PB, T2W/T1W) and mean ± standard deviation, frequency (percent)

position significantly reduced the risk of hemorrhage (OR=0.017, $p<0.001$). Other significant predictors were BWI (OR=58.5, $p<0.001$) and DIB (OR=72.818, $p<0.001$).

As shown in Table 5, CCL ≤ 25.0 mm and S1 ≤ 187.5 cm³ had excellent diagnostic performance (AUC > 0.99, SE 100%, SP > 98%, $p<0.001$), and CCD ≥ 12.0 mm and S2 ≥ 545.3 cm³ also had high predictive value (AUC > 0.98, $p<0.001$).

Table 6 presents intra- and interobserver agreement for various pMRI parameters measured in patients with

placenta previa and PAS, showing almost perfect reliability for most variables. There is nearly perfect agreement between and within observers for cervical canal length (CCL), cervical canal dilatation (CCD), placental localization, S1 and S2 volumes, and other important markers such as bladder wall interruption (BWI) and placental bulge (PB) (all, ≥ 0.998). Parameters such as abnormal vascularity in placental bed (AVPB), focal exophytic mass (FEM), myometrial thickness (MT), and dark intraplacental bands (DIB) also show high reliability, though slightly lower for AVPB and HP (heterogeneous

Table 5 ROC analysis results of variables for severe peripartum hemorrhage

PPH ≥ 2000 mL	Cutoff	AUC (95% CI)	p value	SE	SP	PPV	NPV
CCL (mm)	≤ 25.0	0.996 (0.988 – 1)	< 0.001	100,00%	98.4%	93.3%	100,00%
CCD (mm)	≥ 12.0	0.983 (0.967 – 0.999)	< 0.001	96.4%	95.1%	81.8%	99.2%
S1 (cm ³)	≤ 187.5	0.997 (0.991 – 1)	< 0.001	100,00%	98.4%	93.3%	100,00%
S2 (cm ³)	≥ 545.3	0.99 (0.974 – 1)	< 0.001	96.4%	99.2%	96.4%	99.2%

Abbreviations uterine cervical canal length (CCL, mm), uterine cervical canal dilatation (CCD, mm), placental volume in the upper uterine segment (S1, cm³), placental volume in the lower uterine segment (S2, cm³), the area under the curve (AUC), positive predictive value (PPV), and negative predictive value (NPV)

Table 6 Assessment of intra- and interobserver agreements

Assessment of intra – and interobserver agreements	Intraobserver	Interobserver
CCL (mm)	0.999 (0.998 – 0.999) ^a	0.999 (0.998 – 0.999) ^a
CCD (mm)	0.996 (0.994 – 0.997) ^a	0.998 (0.998 – 0.999) ^a
Localization of placenta (A., P., AL., PL)	1.000 (1.000 – 1.000) ^a	1.000 (1.000 – 1.000) ^a
S1 (cm ³)	1.000 (1.000 – 1.000) ^a	1.000 (1.000 – 1.000) ^a
S2 (cm ³)	1.000 (1.000 – 1.000) ^a	1.000 (1.000 – 1.000) ^a
AVPB (T2W)	0.890 ^b	0.922 ^b
FEM (T2W / T1W)	0.967 ^b	1.000 ^b
BWI (T2W)	1.000 ^b	1.000 ^b
MT (T2W)	0.987 ^b	1.000 ^b
LDPB (T2W)	0.967 ^b	1.000 ^b
PII (T2W/T1W)	1.000 ^b	0.964 ^b
DIB (T2W)	0.959 ^b	1.000 ^b
PB (T2W, T1W)	1.000 ^b	1.000 ^b
HP (T2W/T1W)	0.932 ^b	0.890 ^b

Abbreviations cervical canal length (CCL, mm); uterine cervical canal dilatation (CCD, mm); placental volume in the uterine upper segment (S1, cm³); placental volume in the uterine lower segment (S2, cm³); decreased signal intensity (T1W); areas of increased signal intensity (T2W); abnormal vascularization of the placental bed (AVPB, T2W); placental ischemic infarction (PII, T2W/T1W); heterogeneous placenta (HP, T2W/T1W); focal exophytic mass (FEM, T2W/T1W); bladder wall interruption (BWI, T2W); myometrial thinning (MT, T2W); loss of the thin dark lie beneath the placental bed (LDPB, T2W); dark intraplacental bands (DIB, T2W); placental bulge (PB, T2W/T1W)

placenta). These findings indicate that the pMRI measurements used in this study are highly reproducible, supporting their reliability for clinical use in diagnosing and managing PAS and related conditions.

(For further details on the other results observed in the study, please refer to Supplemental_Contents_1.docx)

Discussion

This study evaluated the predictability of SPPH in pregnant women with cPP accompanied by PAS by measuring the volume of three-dimensional (3D) placental topography using pMRI. Additionally, the contribution of uterine cervical canal length and dilatation measurements on pMRI to the predictability of SPPH was investigated. Our study presents threshold values for placental volume, CCL, and CCD measurements that can predict severe intraoperative hemorrhage in pregnant women with cPP.

Unlike conventional 2D imaging methods, 3D modeling significantly improves preoperative planning for PAS by providing accurate depth perception, which is crucial for understanding the severity and location of abnormal placental adhesion [5]. Our findings highlight that an increased S2 volume is strongly associated with PAS, whereas a decrease in S1 volume demonstrates the high diagnostic potential of PAS with robust sensitivity and specificity.

Patients with PAS and cPP experience increased placental volume due to abnormal trophoblast invasion of the uterine wall and increased vascularity in the placental bed [27]. In cPP patients, the placenta attaches to the lower uterine segment with a limited blood supply. Placental villi grow to compensate for this limitation, thereby increasing the placental volume. This increase in volume improves placental perfusion in patients with cPP [27]. Consequently, owing to vascular supply differences that affect surgical planning and outcomes, the anatomical locations of the uterine sectors (S1 and S2), where pMRI determines the increase in placental volume, are critical in managing PAS.

Yue et al. [27] demonstrated that the placental volume in the PAS group was significantly greater than that in the non-PAS group ($p < 0.05$). This finding was corroborated by a threshold above 887 cm³, which yielded a sensitivity and specificity of 85.531% and 83.907%, respectively, with an AUC of 0.908 (95% CI: 0.853–0.948) [27]. Univariate analysis in our study indicated that an increase in the S2 value was associated with a 1.008-fold increase in PAS risk ($p < 0.001$). This finding was further corroborated by a threshold for S2 above 344.2 cm³, with a yield sensitivity and specificity of 64.1% and 91.5%, respectively, and an AUC of 0.839 (95% CI: 0.772–0.906, $p < 0.001$). A threshold below 491.5 cm³ yielded a sensitivity of 83.5% and specificity of 78.7% for identifying PAS in the S1 sector (AUC: 0.865, 95% CI: 0.802–0.928, $p < 0.001$). Statistical data on placental volume indicate that the finding of a significantly greater placental volume in the PAS group reported by Yue et al. is consistent with the results of the present study. Furthermore, our analysis revealed that high S2 values strongly correlated with the PAS score. In contrast, low S1 values indicate high diagnostic potential for PAS and exhibit strong sensitivity and specificity. This finding reinforces the importance of placental volume as

a predictive marker. Our study revealed that placental volume in the S1 sector is more effective in identifying positive cases because of its high sensitivity. In contrast, the S2 sector provides a complementary benefit in diagnostic evaluation by providing superior specificity.

The difference between our current study and the results of other studies is that we measured placental volume based on placental invasion topography (S1 and S2 sectors) and identified threshold values that could predict maternal morbidity risk. Most earlier studies on placenta previa focused on placental thickness and area [28, 29]. The study by Yue et al. [27] provides a valuable starting point for understanding placental volumetric values. However, the absence of topographic classification for the S1 and S2 sectors underscores the need for further research. In addition, the sector in which placental volume increases is much more valuable in terms of its clinical course and impact on maternal morbidity.

Romeo et al. [30] showed that pMRI is essential for diagnosing and managing patients with PAS, particularly those with cPP. Their study explicitly highlighted that pMRI has a significantly greater accuracy rate in identifying PAS than the combined use of CD-USG and clinical risk factors (CRFs) [30]. The accuracy of pMRI alone was comparable to the combined accuracy of CRF, CD-USG, and pMRI variables (AUC: 0.97) and was more accurate than the accuracy of CRF and CD-USG alone (AUC: 0.83) [30]. While our study did not directly compare the diagnostic performance of CRFs, CD-USG, and pMRI, it aligns with the broader consensus that pMRI is essential for accurately delineating the extent of placental invasion in patients with complete placenta previa. Our findings suggest that pMRI's detailed visualization of placental structures aids in preoperative planning, similar to the insights provided by Romeo et al. [30], even though MRI's high sensitivity can sometimes lead to overcalling PAS. This tendency emphasizes the importance of using MRI as a complementary rather than a standalone diagnostic method. By integrating pMRI results with ultrasound findings, our study supports a balanced approach that leverages MRI's strengths while mitigating the risks of overdiagnosis. This approach is particularly relevant in high-risk PAS cases where accurate identification of invasive placental behavior is critical to reducing maternal morbidity and mortality.

In this context, the AVPB (AUC: 0.750, $p=0.014$), a pMRI marker, has been reported to be a significant determinant of PAS, which supports the results of our study and shows good diagnostic accuracy [31]. In our study, the risk of PAS in patients with AVPB was 28.058 times greater than that in patients without AVPB ($p<0.001$). Additionally, our research showed that the presence of HP and PII on pMRI increased the likelihood of PAS by

37.391 and 23.676 times, respectively, compared to individuals without these features ($p<0.001$, $p=0.002$).

In the literature, women with PAS exhibit more significant intraoperative blood loss (2502.8 ± 718.0 mL vs. 1951.7 ± 685.2 mL) and require more blood product transfusions (1940.4 ± 441.4 mL to 1353.1 ± 582.0 mL, $p<0.001$) [27]. The current study aligns with the literature and reveals an inverse relationship between placental volume in the S1 sector and SPPH (OR: 0.927, 95% CI: 0.87–0.987, $p=0.017$), indicating that a reduced upper segment placental volume is associated with a greater risk of severe hemorrhage. This finding has direct implications for clinical and operative practice, emphasizing the protective role of placental volume in the S1 sector. Conversely, an increased volume in S2 (lower segment placental volume) was strongly correlated with a greater risk of peripartum hemorrhage (OR: 1.032, 95% CI: 1.018–1.047, $p<0.001$), suggesting that a greater volume in this region significantly contributes to adverse outcomes. These findings underscore the importance of comprehensive volumetric assessment for early detection and risk stratification of patients with PAS, thereby improving clinical decision-making and patient management. Our ROC analysis for SPPH showed exceptional diagnostic performance for sectors S1 and S2, with AUC values of 0.997 and 0.99, respectively, underscoring their utility in clinical decision-making. S1 showed perfect sensitivity and high specificity (100% and 98.4%, respectively), while S2 maintained a remarkable balance with high sensitivity and specificity (96.4% and 99.2%, respectively), making both parameters valuable for accurately identifying patients at risk for SPPH.

Research has shown that MT and DIB volume can be reliable indicators for predicting the risk of postpartum hemorrhage in patients with PAS [32]. A negative correlation was observed between MT and blood loss, indicating that a reduction in myometrial thickness is associated with an increased risk of severe postpartum hemorrhage. Conversely, a positive correlation was noted between DIB volume and estimated blood loss, indicating that larger DIB volumes indicate a greater risk of significant blood loss [32]. Another study suggested that specific MRI features, such as intraplacental T2 dark bands, placental bulges, and uteroplacental or parametrial hypervascularity, are significantly associated with clinical outcomes. By identifying these features, it is possible to predict complications such as severe hemorrhage, hysterectomy, or extensive bladder repair, depending on the presence of three or more of these findings [33]. The FIGO classification of the International Criteria for PAS further supports the finding that individuals with significant hemorrhage have greater cPP ($p<0.01$) and anterior localization ($p=0.01$) than those without severe hemorrhage [34]. Our current study is consistent with the

literature and identified six pMRI markers, FEM, BWI, MT, PII, DIB, and PB, which are essential predictors of SPPH in patients with PAS. These markers increased the risk of SPPH to varying degrees, ranging from 23.46- to 72.818-fold ($p < 0.001$).

Measuring the CCL is of utmost importance in predicting and managing complications in pregnant patients with placenta previa complicated by PAS [6]. The correlation between a shorter cervical length and an increased risk of placenta accreta spectrum (PAS) has been supported by various studies, including recent work by Yue et al. [35]. A short cervix may predispose patients to more severe outcomes, such as massive hemorrhage, due to the reduced contractility of the lower uterine segment following placental separation [35, 36]. This area's lack of effective contraction can hinder hemostasis, increasing the risk of significant blood loss during delivery. Moreover, the anatomical proximity of the cervix to regions where placental invasion typically initiates may render it more vulnerable to deeper placental penetration, thereby raising the likelihood of PAS. In our study, cervical length was a significant predictor of PAS, where shorter measurements correlated with increased invasive placental behavior. This finding suggests that careful measurement of cervical length should be considered in assessing patients at high risk for PAS, as it may provide valuable insights into the extent of placental invasion and inform surgical decision-making. Altraigey et al. [6] and Fukushima et al. [37] reported that patients with a $CCL \leq 3$ cm had a significantly greater risk of hemorrhage (> 2000 ml) than those with a $CCL > 3$ cm. This finding is paramount for understanding the correlation between the CCL and SPPH. Using ROC analysis, Polat et al. [38] reported using a minimum of four units of RBC suspension in placenta percreta patients with pTAH and obtained an accurate CCL value of 2.05 cm. This level of measurement precision is critical for understanding the relationship between CCL and SPPH. Mimura et al. [39] reported a negative correlation between CCL and hemorrhage in patients with placenta previa ($r = -0.344$, $p < 0.001$). This means that as the CCL decreases, the risk of hemorrhage increases. According to the ROC curve, a CCL of 2.5 cm was associated with blood loss above 2500 mL. This suggests that a CCL value of < 2.5 cm can be a threshold for high-risk patients. Dang et al. [7] revealed a straight-line link between CCL and SPPH, with a more noticeable change in OR at $CCL \leq 2.5$ cm. Zhou et al. [10] revealed the increased maternal and neonatal risks associated with large placental areas and short CCLs and provided practical implications. Accordingly, larger placental areas and shorter CCLs are associated with longer surgery times, increased intraoperative blood loss, and transfusions [10]. Placental areas greater than 50 cm^2 can identify 87% of high-risk SPPH cases during C/S and 92%

of low-risk cases with an AUC of 0.907 [10]. Similarly, a CCL less than 30 mm had a sensitivity and specificity of 87% and 91%, respectively, in identifying patients at high risk for SPPH at C/S, with an AUC of 0.895 [10].

In line with the literature, our study revealed that CCL and CCD were critical determinants of SPPH. CCL, a frequently evaluated factor, showed an inverse association with the risk of hemorrhage, with a longer channel length associated with a lower risk of severe hemorrhage (OR: 0.406, 95% CI: 0.214 to 0.77, $p = 0.006$). However, the importance of CCD has yet to be determined. This finding represents a unique contribution to the literature and reveals an additional novel method for patients undergoing pMRI.

In contrast to CCL, CCD values were positively correlated with the risk of SPPH. Therefore, more significant cervical dilation increased the likelihood of severe bleeding (OR: 3.22, 95% CI: 1.97–5.262; $p < 0.001$). These findings underscore the importance of assessing cervical morphology as part of the risk stratification process for patients with PAS and provide valuable insights for clinical decision-making and patient management. Our study presents a promising avenue for SPPH management, highlighting the potential benefits of uterine CCL and CCD measurements. Specifically, a $CCL \leq 25$ mm and $CCD \geq 12$ mm showed high diagnostic accuracy, with AUC values of 0.996 and 0.983, respectively. These measurements can significantly enhance the identification of high-risk patients, leading to timely interventions and improved maternal outcomes.

Strengths of the study

This retrospective study offers several significant strengths that enhance its contribution to the field of prenatal diagnosis and management of PAS. One of the primary strengths lies in the three-dimensional (3D) topographic examination of the placenta and the precise measurement of placental volume within the S1 and S2 uterine sectors using pMRI. These advanced imaging techniques allow for establishing novel cutoff values that predict the risk of PAS and SPPH. To our knowledge, no prior studies have addressed this specific approach, making our findings particularly valuable for clinical practice. Additionally, this study is the first to establish cutoff values for measuring CCL using MRI as a predictor for PAS and SPPH, providing a new perspective on risk assessment that has not been explored previously. Moreover, the study's establishment of cutoff values for the correlation between the CCD and the risk of SPPH due to PAS further adds to its novelty, filling a critical gap in the existing literature.

Despite being conducted in a single center, the study involves a substantial cohort, allowing for robust statistical analysis and improving the generalizability of

the findings. The research team also assesses intra- and interobserver agreements, ensuring the reliability and consistency of imaging measurements and interpretations. Furthermore, the study carefully situates its findings within existing literature, offering a thorough comparison with previous research while emphasizing its novel contributions. This comprehensive approach strengthens the study's conclusions and highlights its potential to inform future research and clinical strategies for managing patients at high risk of PAS and SPPH.

Limitations

This study had several limitations, including its single-center retrospective design, limited sample size, and model development at a single time point during pregnancy. Future research should involve multicenter prospective studies to confirm the diagnostic feasibility of measuring placental volume, cervical canal length, and cervical canal dilation. Our study focused on establishing cutoff values for absolute volume measurements in the S1 and S2 regions to predict PAS and SPPH risk. However, we did not explore using a ratio between S1 and S2 volumes. Future studies could investigate whether such a ratio might provide additional predictive value, particularly concerning gestational age differences between PAS-positive and PAS-negative patients.

Conclusion

In conclusion, our study results suggest that pMRI indicators, such as the CCL, CCD, S1, and S2, are reliable predictors of the PAS and SPPH. Precise anticipation of these indicators will enable more efficient surgical interventions and intraoperative treatment planning. This highlights the importance of pMRI in the treatment of PAS, as it not only aids in the preoperative identification of the condition but also allows for an estimation of the complexity of the surgery and the probable requirement for blood transfusions, thus enhancing patient outcomes.

Abbreviations

ACOG	The American College of Obstetricians and Gynecologists
ACR	The American College of Radiology
AVPB	Abnormal vascularization of the placental bed (T2W)
BTFE	Balanced turbo field-echo
BWI	Bladder wall interruption (T2W)
CCL	Cervical canal length
CCD	Cervical canal dilatation
CD-USG	Color Doppler ultrasonography
CI	Confidence interval
cPP	Complete placenta previa
C/S	Cesarean section
DIB	Dark intraplacental bands (T2W)
ESUR	The European Society of Urogenital Radiology
FFP	Fresh frozen plasma
FIGO	International Federation of Gynecology and Obstetrics
FEM	Focal exophytic mass (T2W/T1W)
HP	Heterogeneous placenta (T2W/T1W)
IS-AIP	The International AIP Society
LDPB	Loss of the thin dark line beneath the placental bed (T2W)

MDT	Multidisciplinary team
MRI	Magnetic resonance imaging
MT	Myometrial thinning (T2W)
OR	Odds ratio
PAS	Placenta accreta spectrum
PB	Placental bulge (T2W/T1W)
PII	Placental ischemic infarction (T2W/T1W)
pMRI	Placental magnetic resonance imaging
RBCs	Red blood cells
ROC	Receiver operating characteristic
SAR	The Society of Abdominal Radiology
S1	Placental volume in the uterine upper segment (cm ³)
S2	Placental volume in the uterine lower segment (cm ³)
SPPH	Severe peripartum hemorrhage
T1W	Decreased signal intensity
T2W	Areas of increased signal intensity
TR	Repetition time
3D	Three-dimensional

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12884-024-06996-w>.

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Author contributions

S.K: Conceptualization, methodology, writing - original draft, writing - review and editing, project administration. S.A: Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Data curation. Ç.G: Data curation, methodology, writing - original draft, validation, and supervision. O.D: analyzed the imaging data. All authors reviewed the manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

All patients signed informed consent forms, and this study received approval from the Scientific Research Ethics Committee of Adana City Training and Research Hospital (Approval No. 1428, June 2, 2021).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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