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Uterine Artery Doppler Indices and Endometrial Blood Flow Zones as Predictors of Clinical Pregnancy in Frozen Embryo Transfer Cycles: A Prospective Observational Study from a Tertiary Care Centre in Rajasthan, India

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Abstract
Background: Endometrial receptivity is a critical determinant of implantation success in frozen embryo transfer (FET) cycles. Colour Doppler ultrasound provides a non-invasive means of assessing uterine artery haemodynamics and endometrial vascularity. Data on optimal Doppler threshold values specific to the Indian FET population remain limited. ***Methods:*** This prospective observational study enrolled 88 infertile women aged 21–40 years undergoing hormone replacement therapy (HRT)-FET cycles at NIMSR and Eva Clinic, Jaipur, Rajasthan, over 18 months. Colour Doppler assessment of uterine artery pulsatility index (PI), resistance index (RI), and peak systolic velocity (PSV), along with endometrial blood flow (EBF) zone classification (Zones 1–4) and endometrial thickness (ET), was performed on the day of confirmed endometrial readiness (ET ≥7 mm, trilaminar pattern) before progesterone initiation. The primary outcome was clinical pregnancy, defined as an intrauterine gestational sac with fetal cardiac activity on ultrasound at 6–8 weeks. Receiver operating characteristic (ROC) curve analysis and multivariate logistic regression were applied. ***Results:*** The overall clinical pregnancy rate (CPR) was 35.2% (31/88). Women who achieved clinical pregnancy had significantly lower mean uterine artery PI (1.82±0.31 vs. 2.31±0.42; p<0.001), lower RI (0.68±0.08 vs. 0.79±0.09; p<0.001), higher PSV (38.4±7.2 vs. 28.6±8.1 cm/s; p<0.001), and greater ET (9.2±1.1 vs. 8.4±1.3 mm; p=0.004). Deeper endometrial vascular penetration (Zones 3+4) was significantly more frequent in the pregnant group (67.7% vs. 38.6%; p=0.009), with a dose-response: CPR ranged from 15.4% (Zone 1) to 58.3% (Zone 4). ROC analysis identified PI ≤2.05 as the optimal single cutoff (AUC=0.823; sensitivity 80.6%; specificity 78.9%; NPV 90.2%). A combined PI + ET model achieved the highest predictive accuracy (AUC=0.871; sensitivity 83.9%; specificity 84.2%). Multivariate logistic regression confirmed PI (OR=0.159; p<0.001), RI (OR=0.000270; p=0.003), EBF Zone 3+4 (OR=4.137; p=0.005), and ET (OR=1.462; p=0.035) as independent predictors of clinical pregnancy. ***Conclusion:*** Uterine artery PI ≤2.05 and deeper endometrial blood flow (Zones 3 and 4) are significant independent predictors of clinical pregnancy in FET cycles. The combined PI + ET model provides superior predictive accuracy (AUC=0.871). Routine colour Doppler assessment should be integrated into pre-transfer ultrasound evaluation to improve patient counselling and guide individualised management in FET cycles.

Keywords: frozen embryo transfer; uterine artery Doppler; pulsatility index; endometrial blood flow; endometrial receptivity; colour Doppler ultrasound; clinical pregnancy rate.

INTRODUCTION
Infertility is a significant global reproductive health burden, affecting an estimated 48 million couples worldwide. In India, the prevalence of infertility ranges from 3.9% to 16.8%, with urban centres such as Jaipur, Rajasthan, experiencing disproportionately high demand for assisted reproductive technology (ART) services, driven by rising rates of polycystic ovary syndrome (PCOS), endometriosis, and tubal disease alongside delayed childbearing. [AUTHOR QUERY: verify WHO/ICMR infertility prevalence reference]

Frozen embryo transfer (FET) has become the dominant ART strategy in contemporary practice, driven by advances in vitrification, the adoption of ‘freeze-all’ protocols to mitigate ovarian hyperstimulation syndrome (OHSS) risk, and improved post-thaw embryo survival rates exceeding 95%. Despite standardised hormone replacement therapy (HRT)-

based endometrial preparation, clinical pregnancy rates per FET cycle remain variable at 25–45% across centres, reflecting the challenge of accurately predicting and optimising endometrial receptivity at the individual level.[1]

Effective implantation requires precise synchrony between a developmentally competent embryo and a receptive endometrium during the window of implantation. Endometrial receptivity is conventionally assessed by transvaginal ultrasonography, with endometrial thickness (ET) and the trilaminar morphological pattern as the principal sonographic markers. However, the predictive value of ET alone in the clinically acceptable range (7–14 mm) is limited and does not capture the haemodynamic dimension of endometrial receptivity.[2]

Colour Doppler ultrasound enables non-invasive, real-time assessment of uterine artery haemodynamics — principally the pulsatility index (PI), resistance index (RI), and peak systolic velocity (PSV) — as well as endometrial blood flow (EBF) patterns. Lower uterine artery impedance indices reflect reduced vascular resistance and enhanced uterine perfusion, prerequisites for adequate endometrial vascularisation and implantation.[2] Studies in IVF and FET cycles have identified uterine artery PI and EBF zone as informative markers of endometrial receptivity.[3–5]

Despite accumulating evidence, comprehensive data from Indian FET populations remain sparse. Regional differences in patient demographics, PCOS prevalence, BMI distribution, and institutional ART protocols may limit the direct applicability of internationally derived Doppler threshold values. This study was designed to prospectively evaluate the role of colour Doppler indices and EBF zone classification in predicting clinical pregnancy in HRT-FET cycles at a tertiary ART centre in Jaipur, and to derive population-specific optimal cutoff values for clinical use

MATERIALS AND METHODS

Study Design and Setting

This prospective observational study was conducted at the Department of Reproductive Medicine and Surgery, National Institute of Medical Sciences & Research (NIMSR), and Eva Clinic (Unit of NIMS), Jaipur, Rajasthan, India, over an 18-month period. Ethical approval was obtained from the Institutional Ethics Committee, NIMSR. [AUTHOR QUERY: insert IEC reference number and approval date.] Written informed consent was obtained from all participants prior to enrolment.

Participants

Infertile women aged 21–40 years undergoing HRT-FET cycles were eligible. Inclusion criteria comprised: good-quality frozen embryos available for transfer, ET ≥7 mm with a trilaminar or multi-layered echogenic pattern on transvaginal ultrasound, and anti-Müllerian hormone (AMH) >1.5 ng/mL. Exclusion criteria encompassed uterine structural anomalies (bicornuate or septate uterus, cavity-distorting fibroids), endometrial pathology (genital tuberculosis, Asherman syndrome), thin endometrium (<7 mm despite adequate hormonal preparation), systemic disorders (hypertension, autoimmune or thrombophilic conditions), oocyte donation cycles, surrogacy, and severe male factor infertility. The final analysed sample comprised 88 women.

Sample Size

Sample size was calculated using the formula $n = Z^2pq/l^2$, where Z = 1.96 (95% confidence level), p = 0.75 (estimated prevalence of favourable endometrial haemodynamics in the target population), q = 0.25, and l = 0.10 (absolute precision), yielding n = 88 subjects.

Endometrial Preparation Protocol

All participants underwent a standardised HRT cycle. A baseline transvaginal ultrasound was performed on cycle day 2–3 to confirm quiescent ovaries and baseline ET ≤5 mm. Estradiol valerate 6 mg/day orally (2 mg three times daily) was commenced from day 2–3. Follow-up ultrasound was performed on day 10–11. When ET ≥7 mm with a trilaminar pattern was confirmed, progesterone 100 mg intramuscularly daily was initiated. Cleavage-stage embryos (day 3) were transferred on day 3, and blastocysts on day 5 of progesterone supplementation.

Colour Doppler Assessment

Colour Doppler assessment was performed on the day of confirmed endometrial readiness (ET ≥7 mm, trilaminar pattern), coinciding with progesterone initiation, using a high-resolution 6.7 MHz transvaginal transducer. Uterine artery waveforms were obtained bilaterally from the ascending branches at the level of the internal os; three consecutive waveforms were averaged. PI, RI, and PSV were recorded bilaterally, and mean values calculated. Endometrial blood flow was assessed by colour Doppler energy (power Doppler) in sagittal and transverse planes, with the full endometrium visualised. Vascular penetration was classified into: Zone 1 (no flow, or flow confined to the outer myometrium), Zone 2 (flow reaching the outer endometrium or subendometrial zone), Zone 3 (flow penetrating the inner endometrium), and Zone 4 (flow reaching the central endometrial cavity). For binary analyses, Zones 3 and 4 were classified as ‘favourable’ and Zones 1 and 2 as ‘unfavourable’.

Outcome Measures

The primary outcome was clinical pregnancy, defined as ultrasound confirmation of an intrauterine gestational sac with fetal cardiac activity at 6–8 weeks of gestation. Secondary outcomes included EBF zone distribution between groups, ROC-derived diagnostic accuracy of Doppler parameters and ET, optimal cutoff values by maximum Youden Index, and independent predictors of clinical pregnancy on multivariate logistic regression.

Statistical Analysis

Continuous variables are presented as mean ± standard deviation and compared between groups by Student's t-test. Categorical variables are expressed as frequencies and percentages and compared by chi-square or Fisher's exact test as appropriate. Spearman correlation was used to assess associations between Doppler indices and study parameters. ROC curve analysis determined AUC and optimal cutoff values (maximum Youden Index). Multivariate logistic regression included variables significant on univariate analysis. DeLong's method was applied for AUC comparison. Statistical significance was set at $p<0.05$. All analyses were performed using SPSS version 23.

RESULTS

Baseline Characteristics

A total of 88 women were enrolled: 31 achieved clinical pregnancy (pregnant group) and 57 did not (non-pregnant group). The groups were comparable for all baseline demographic and clinical variables (Table 1). Mean age was 29.6±3.8 years in the pregnant group vs. 30.8±4.2 years in the non-pregnant group (p=0.168). BMI, duration and type of infertility, AMH, TSH, and number of prior ART cycles did not differ significantly between groups (all p>0.05). PCOS was the most common cause of infertility (28.4%), followed by tubal factor (21.6%) and unexplained infertility (20.5%); the distribution did not differ significantly between groups (χ^2=0.19; p=0.979).

Table 1. Baseline Demographic and Clinical Characteristics

Variable	Pregnant (n=31)	Non-Pregnant (n=57)	p-value
Age (years, mean ± SD)	29.6 ± 3.8	30.8 ± 4.2	0.168
BMI (kg/m², mean ± SD)	[AUTHOR QUERY]	[AUTHOR QUERY]	NS
Duration of infertility (years)	[AUTHOR QUERY]	[AUTHOR QUERY]	NS
AMH (ng/mL, mean ± SD)	[AUTHOR QUERY]	[AUTHOR QUERY]	NS
TSH (mIU/L, mean ± SD)	[AUTHOR QUERY]	[AUTHOR QUERY]	NS
Prior ART cycles (mean ± SD)	[AUTHOR QUERY]	[AUTHOR QUERY]	NS
PCOS (%)	[AUTHOR QUERY]	[AUTHOR QUERY]	
Tubal factor (%)	[AUTHOR QUERY]	[AUTHOR QUERY]	
Unexplained infertility (%)	[AUTHOR QUERY]	[AUTHOR QUERY]	

NS = not significant (all p>0.05). AMH = anti-Müllerian hormone; BMI = body mass index; ART = assisted reproductive technology; PCOS = polycystic ovary syndrome. [AUTHOR QUERY: fill in group-specific mean values from thesis Table 5.1.]

Clinical Pregnancy Rate and Outcomes

The overall CPR was 35.2% (31/88 cycles) and the ongoing pregnancy rate was 25.0% (22/88). A positive biochemical pregnancy (β-hCG ≥5 mIU/mL at 12–14 days post-transfer) was recorded in 33 women (37.5%), of whom 31 (93.9%) had a confirmed intrauterine gestational sac. Among the 31 clinical pregnancies, 22 (71.0%) progressed to an ongoing pregnancy at 10–12 weeks, 5 (16.1%) resulted in early clinical miscarriage, 2 (6.5%) had biochemical miscarriage, and 1 (3.2%) was diagnosed with ectopic pregnancy.

Endometrial Parameters

Endometrial thickness was significantly greater in the pregnant group (9.2±1.1 mm vs. 8.4±1.3 mm; t=2.98; p=0.004). The trilaminar (Pattern A) endometrial morphology was significantly more prevalent in the pregnant group (71.0% vs. 45.6%; χ^2=6.82; p=0.033), while the homogeneous echogenic pattern (Pattern C) was more common in the non-pregnant group (17.5% vs. 6.5%).

Uterine Artery Doppler Parameters

All uterine artery Doppler indices differed highly significantly between groups (all p<0.001). The pregnant group demonstrated lower mean PI (1.82±0.31 vs. 2.31±0.42), lower mean RI (0.68±0.08 vs. 0.79±0.09), and higher mean PSV (38.4±7.2 vs. 28.6±8.1 cm/s). Effect sizes (Cohen's d) ranged from 1.27 to 1.59, indicating large clinical differences. Both left and right uterine artery indices showed consistent and significant differences between groups (Table 2).

Table 2. Uterine Artery Doppler Indices: Comparison Between Groups

Parameter	Pregnant (n=31)	Non-Pregnant (n=57)	p-value	Cohen's d
Mean PI (mean ± SD)	1.82 ± 0.31	2.31 ± 0.42	<0.001	1.38
Mean RI (mean ± SD)	0.68 ± 0.08	0.79 ± 0.09	<0.001	1.31
Mean PSV (cm/s, mean ± SD)	38.4 ± 7.2	28.6 ± 8.1	<0.001	1.27

PI = pulsatility index; RI = resistance index; PSV = peak systolic velocity. Values are mean ± SD.

Endometrial Blood Flow Zone Distribution

The distribution of EBF zones differed significantly between groups (χ^2=9.34; p=0.025) (Table 3). Zone 1 (absent endometrial flow) was observed in 6.5% of pregnant vs. 19.3% of non-pregnant women. Zones 3 and 4 (deep vascular penetration) were observed in 45.2% and 22.6% of pregnant women respectively, compared to 29.8% and 8.8% in non-pregnant women. When dichotomised, favourable EBF (Zones 3+4) was significantly more frequent in the pregnant group (67.7% vs. 38.6%; χ^2=6.84; p=0.009; OR=3.27; 95% CI: 1.22–8.75).

A clear dose-response relationship was observed between EBF zone depth and CPR: Zone 1: 15.4%; Zone 2: 25.0%; Zone 3: 45.2%; Zone 4: 58.3% (Table 3). Women with Zone 4 flow had significantly higher odds of clinical pregnancy compared to Zone 1 (OR=7.58; 95% CI: 1.23–46.7; p=0.029).

Table 3. Endometrial Blood Flow Zone Distribution and Clinical Pregnancy Rates

EBF Zone	Pregnant n (%)	Non-Pregnant n (%)	CPR (%)	OR (95% CI)
Zone 1 (absent flow)	2 (6.5%)	11 (19.3%)	15.4%	Reference
Zone 2 (outer EBF)	8 (25.8%)	24 (42.1%)	25.0%	1.93 (0.37–10.1)
Zone 3 (inner EBF)	14 (45.2%)	17 (29.8%)	45.2%	4.12 (0.81–21.0)
Zone 4 (central flow)	7 (22.6%)	5 (8.8%)	58.3%	7.58 (1.23–46.7)*
Zones 3+4 (favourable)	21 (67.7%)	22 (38.6%)	48.8%	3.27 (1.22–8.75)*

EBF = endometrial blood flow; CPR = clinical pregnancy rate; OR = odds ratio; CI = confidence interval. *p<0.05. Fisher's exact test applied for cells with small expected frequencies.

ROC Curve Analysis

ROC curve analysis demonstrated that mean uterine PI had the highest AUC among individual parameters (Table 4). At the optimal cutoff of PI ≤2.05, sensitivity was 80.6%, specificity 78.9%, PPV 63.3%, and NPV 90.2% (AUC=0.823; 95% CI: 0.730–0.916). Mean RI (AUC=0.791) and PSV (AUC=0.762) were the next most discriminatory single parameters. The combined PI + ET model provided the highest predictive accuracy (AUC=0.871; 95% CI: 0.786–0.956), representing a statistically significant improvement over PI alone (DeLong z=1.97; p=0.049). The high NPV of 90.2% indicates that women with PI ≤2.05 are very unlikely to experience failed implantation due to uterine haemodynamic insufficiency.

Table 4. ROC Curve Analysis: Diagnostic Accuracy of Doppler Parameters for Predicting Clinical Pregnancy

Parameter	AUC (95% CI)	Optimal Cutoff	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
Mean PI	0.823 (0.730–0.916)	≤2.05	80.6	78.9	63.3	90.2
Mean RI	0.791	≤0.725	74.2	77.2	[AQ]	[AQ]
Mean PSV	0.762	≥33.0 cm/s	[AQ]	[AQ]	[AQ]	[AQ]
ET	0.683	≥8.75 mm	64.5	66.7	[AQ]	[AQ]
EBF zone	0.645	Zone 3+4 vs 1+2	[AQ]	[AQ]	[AQ]	[AQ]
PI + ET combined	0.871 (0.786–0.956)	PI ≤2.05 + ET ≥8.75 mm	83.9	84.2	[AQ]	92.3

AUC = area under ROC curve; PPV = positive predictive value; NPV = negative predictive value; PI = pulsatility index; RI = resistance index; PSV = peak systolic velocity; ET = endometrial thickness; EBF = endometrial blood flow. [AQ] = Author Query: please supply exact values from thesis Table 5.10.

Multivariate Logistic Regression

Multivariate logistic regression identified four independent predictors of clinical pregnancy (Table 5). Mean uterine PI was the strongest single predictor: each unit increase in PI reduced the odds of clinical pregnancy by 84.1% (OR=0.159; 95% CI: 0.062–0.409; $p<0.001$). Mean RI was also independently predictive (OR=0.000270; 95% CI: 0.000001–0.058; $p=0.003$). The presence of Zone 3+4 EBF approximately quadrupled the odds of pregnancy compared to Zone 1+2 (OR=4.137; 95% CI: 1.524–11.23; $p=0.005$). Each additional millimetre of ET increased the odds by 46.2% (OR=1.462; 95% CI: 1.024–2.088; $p=0.035$). The model demonstrated excellent performance: Nagelkerke $R^2=0.512$, correct classification accuracy 80.7%, and good calibration (Hosmer–Lemeshow $p=0.613$).

Table 5. Multivariate Logistic Regression: Independent Predictors of Clinical Pregnancy in FET Cycles

Variable	OR	95% CI	p-value
Mean uterine artery PI	0.159	0.062–0.409	<0.001
Mean uterine artery RI	0.000270	0.000001–0.058	0.003
EBF Zone 3+4 (vs. Zone 1+2)	4.137	1.524–11.23	0.005
Endometrial thickness (per 1 mm)	1.462	1.024–2.088	0.035

OR = odds ratio; CI = confidence interval; PI = pulsatility index; RI = resistance index; EBF = endometrial blood flow. Model fit: Nagelkerke $R^2=0.512$; correct classification 80.7%; Hosmer–Lemeshow $p=0.613$.

Correlation Analysis

Mean uterine PI showed a moderate inverse correlation with ET ($r=-0.412$; $p<0.001$) and with EBF zone (Spearman $\rho=-0.448$; $p<0.001$). Mean RI correlated inversely with ET ($r=-0.387$; $p<0.001$) and EBF zone ($\rho=-0.419$; $p<0.001$). Mean PSV correlated positively with ET ($r=+0.363$; $p<0.001$). PI and RI were strongly correlated ($r=+0.741$; $p<0.001$). No significant associations were found between uterine PI and patient age or BMI

DISCUSSION

This prospective observational study of 88 infertile women undergoing HRT-FET cycles demonstrates that colour Doppler assessment of uterine artery haemodynamics and endometrial vascularity provides clinically meaningful, independent predictive information for clinical pregnancy outcome beyond standard morphological assessment. The principal findings are: (1) women achieving clinical pregnancy showed significantly lower uterine artery PI and RI, and higher PSV; (2) deeper EBF penetration (Zones 3 and 4) was associated with improved CPR in a dose-response fashion; (3) uterine PI ≤2.05 was the most discriminatory single Doppler parameter (AUC=0.823); (4) a combined PI + ET model achieved the highest predictive accuracy (AUC=0.871); and (5) PI, RI, EBF zone, and ET were confirmed as independent predictors on multivariate analysis.

Clinical Pregnancy Rate

The CPR of 35.2% observed in this study is consistent with published benchmarks for HRT-FET cycles in comparable patient populations, where CPR typically ranges from 25–45%. Bahrami et al. reported comparable clinical pregnancy outcomes in an Iranian FET cohort assessed with uterine artery Doppler and endometrial perfusion.[1] The ongoing pregnancy rate of 25.0% is also in line with published Indian and international FET series, confirming that the study population and institutional performance are representative of the target clinical setting.

Uterine Artery Doppler Indices

The significant difference in mean PI between pregnant (1.82±0.31) and non-pregnant women (2.31±0.42; $p<0.001$) observed in this study is consistent with prior investigations. Zaidi et al. were among the first to demonstrate in 96 IVF-ET cycles that absent subendometrial and intraendometrial blood flow was invariably associated with implantation failure, while detectable endometrial vascularisation was associated with significantly higher pregnancy rates ($p<0.05$).[2] Tekay et al. similarly confirmed that absent end-diastolic flow in uterine arteries was universally associated with implantation failure in both frozen and fresh embryo transfer cycles.[3] More recently, Bahrami et al. demonstrated that PI was the most discriminatory Doppler parameter in a prospective FET cohort, consistent with the present findings,[1] and Fan et al. showed that uterine artery Doppler parameters during the implantation window add predictive value for the first FET beyond standard clinical variables.[5]

The mean RI of 0.68±0.08 in pregnant vs. 0.79±0.09 in non-pregnant women ($p<0.001$) is consistent with the commonly cited RI threshold of ≤0.75 for favourable uterine haemodynamics in ART. Yu et al. reported significantly lower uterine artery RI in frozen-thawed ET cycles, associated with superior CPR, implantation rate, and live birth rate compared to fresh transfer.[6] The moderate inverse correlation between PI and ET ($r=-0.412$; $p<0.001$) suggests that adequate endometrial proliferation is partly a haemodynamic phenomenon, mediated by oestrogen-driven vasodilatation.

Optimal Doppler Cutoffs and Diagnostic Accuracy

ROC analysis identified PI ≤2.05 as the optimal threshold for this Indian FET population (AUC=0.823; NPV 90.2%). The high NPV is of particular clinical relevance: women with PI ≤2.05 can be reassured that haemodynamic endometrial insufficiency is an unlikely cause of implantation failure, while those with PI >2.05 may be candidates for interventions aimed at improving uterine perfusion — such as low-dose aspirin, sildenafil, or pentoxifylline — pending evaluation in future randomised controlled trials.

The combined PI + ET model (AUC=0.871; sensitivity 83.9%; specificity 84.2%) demonstrated a statistically significant improvement over PI alone (DeLong $p=0.049$). Bahrami et al. similarly reported that combining ET with uterine artery PI improved predictive accuracy in FET cycles.[1] These findings support a multiparameter approach to endometrial assessment in clinical practice.

Endometrial Blood Flow Zones

The dose-response relationship between EBF zone depth and CPR (Zone 1: 15.4%; Zone 2: 25.0%; Zone 3: 45.2%; Zone 4: 58.3%) is consistent with the biological premise that increasing depth of endometrial vascularisation reflects progressively greater receptivity. Zaidi et al. first demonstrated in IVF cycles that absent endometrial colour flow was universally associated with implantation failure, while intraendometrial vascular penetration was significantly associated with higher pregnancy rates.[2] Zang et al. confirmed in a large FET cohort that subendometrial blood flow detectability was independently associated with embryo implantation, even in patients with thin endometrium.[7] In the present study, Zone 3+4 EBF was an independent predictor of pregnancy after adjusting for PI, RI, and ET (OR=4.137; $p=0.005$), extending these findings to a standard-thickness FET population.

Endometrial Thickness and Pattern

Although ET was significantly greater in the pregnant group (9.2±1.1 vs. 8.4±1.3 mm; $p=0.004$) and emerged as an independent predictor on multivariate analysis (OR=1.462 per mm; $p=0.035$), its AUC of 0.683 was substantially lower than all Doppler parameters. This confirms the well-established limitation of ET as a sole predictor of implantation success in the clinically acceptable range. The trilaminar pattern was more prevalent in the pregnant group (71.0% vs. 45.6%; $p=0.033$) but did not retain independent significance on multivariate analysis, suggesting that Doppler indices capture additional variance in implantation success beyond morphological appearance.

Strengths and Limitations

Strengths include a prospective design with standardised protocols, simultaneous comprehensive assessment of both uterine artery indices and EBF zones, a priori sample size calculation, and the derivation of Indian FET-specific Doppler threshold values. Limitations include single-centre design, a sample size of 88 that may be underpowered for some secondary analyses, restriction to qualitative 2D colour Doppler without three-dimensional quantitative indices (vascularisation index, flow index, vascularisation-flow index), and the absence of live birth data as a primary endpoint. Future multicentre randomised trials are warranted to validate these thresholds and evaluate whether Doppler-guided interventions improve live birth rates

CONCLUSION

Colour Doppler ultrasound assessment of uterine artery indices and endometrial blood flow provides clinically meaningful, independent predictive information for clinical pregnancy in frozen embryo transfer cycles. A uterine artery PI ≤2.05 is the optimal single Doppler threshold for this Indian FET population (AUC=0.823; NPV 90.2%), and a combined PI + ET model achieves superior accuracy (AUC=0.871; NPV 92.3%). Deeper endometrial vascular penetration (Zones 3 and 4) independently quadruples the odds of clinical pregnancy. These findings support the routine integration of colour Doppler evaluation — including PI, RI, PSV, and EBF zone classification — into the pre-transfer ultrasound assessment in FET cycles. Women with PI >2.05 or Zone 1 EBF should be considered for individualised counselling and adjuvant interventions to optimise uterine blood flow prior to embryo transfer.

Declarations

Ethics Approval and Consent to Participate: The study was approved by the Institutional Ethics Committee, NIMSR, Jaipur [AUTHOR QUERY: insert IEC reference number and date of approval]. Written informed consent was obtained from all participants prior to enrolment.

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Author Contributions: [AUTHOR QUERY: specify individual author contributions per the CRediT taxonomy.]

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Data Availability: De-identified data supporting the findings of this study are available from the corresponding author on reasonable request.

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