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# Research on Establishing a Prediction Model for Pregnancy Outcomes Based on Retrospective Analysis of 1,131 Cases of Frozen-Thawed Single Embryo Transfer

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**Abstract:** *Objective:* This study is based on preliminary clinical data from a public welfare project funded by the Jinhua Science and Technology Bureau. A total of 1,131 cases of frozen-thawed single embryo transfer were retrospectively enrolled to investigate clinical indicators such as patient age, embryo developmental stage, and endometrial type. Key factors influencing pregnancy outcomes were identified, and a predictive model was constructed. This provides a prerequisite for analyzing the correlation between the immune functional status of Treg lymphocytes and pregnancy outcomes following embryo transfer, and also serves as a reference for clinical immune assessment and individualized embryo transfer strategies in assisted reproduction. This research intends to set up a pregnancy outcome prediction model relying on 1131 frozen-thawed single embryo transfer instances. It takes into account elements like patients age, d3 embryo transfer, d4 fused embryo, d5 or d6 blastocyst, endometrial thickness and type, etc. *Methods:* Via systematic data gathering, which encompasses fundamental patient details, data associated with embryo development, and endometrial data, and by utilizing statistical instruments like SPSS and R software for univariate analysis and multivariate logistic regression analysis, independent factors influencing pregnancy results were screened. Based on this situation, a prediction model for pregnancy outcomes was built by using a nomogram. *Results:* Validated through ROC curves and AUC values, the model showed good discriminatory ability and calibration, efficiently forecasting the pregnancy result of single embryo transfer and offering a significant reference for clinical decision-making. *Conclusion:* It is feasible to set up a pregnancy outcome prediction model for single embryo transfer, and it has high precision.

**Keywords:** Single embryo transfer; Pregnancy outcome; Prediction model; Endometrial thickness; Embryo development

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# 1. Introduction

## 1.1. Research

Background With the continuous advancement of assisted reproductive technology, Single Embryo Transfer (SET) has emerged as one of the primary strategies for optimizing pregnancy outcomes. Its significance in enhancing pregnancy rates while substantially reducing the risk of multiple pregnancies has become increasingly evident [1]. Recent outcomes from selective SET practices during Frozen Embryo Transfer (FET) cycles indicate that this strategy can achieve high clinical pregnancy and implantation rates in specific populations, particularly for women under 33 years of age, where Day 5 Blastocyst Transfer (SBT-D5) demonstrates superior advantages compared to other protocols [2]. Furthermore, research on nomogram-based predictive models for clinical pregnancy in single-blastocyst transfer during thaw cycles underscores the importance of precise prediction. This study selects independent influencing factors through multivariate regression analysis, providing a scientific basis for formulating individualized treatment plans [3]. However, the dynamic compatibility between endometrial receptivity and embryo quality remains a primary factor influencing pregnancy outcomes. The complexity of this compatibility significantly increases prediction challenges, especially across different age groups and embryo types [4,5]. Therefore, constructing a pregnancy outcome prediction model that integrates multiple key factors not only facilitates the optimization of embryo transfer protocols but also provides clinicians with more accurate decision-making references. Although SET has demonstrated notable success in assisted reproductive technology, current research on pregnancy outcome prediction still faces significant limitations. Most studies focus on single-factor or limited-variable analyses, with insufficient in-depth exploration of the synergistic effects of multiple factors [6,7]. For example, although existing studies have shown that endometrial thickness and embryo type play major roles in pregnancy outcomes, such research often fails to fully account for the interplay of multiple factors, including patient age, embryo development rate, and endometrial type [8]. Furthermore, the discrimination and calibration of existing predictive models still require improvement; in particular, the applicability of traditional statistical methods is significantly limited when dealing with non-normally distributed data [7]. Thus, constructing a predictive model that comprehensively incorporates factors such as patient age, Day 3 embryo transfer status, Day 5/6 blastocyst development, endometrial thickness, and type plays a crucial role in enhancing the accuracy of pregnancy outcome predictions and their clinical relevance.

## 1.2. Research objectives

This study aims to construct a pregnancy outcome prediction model based on 1,131 SET cases, incorporating factors such as patient age, Day 3 embryo transfer status, Day 5/6 blastocyst development, endometrial thickness, and type. Through systematic analysis of these key factors, the study seeks to determine their independent and interactive effects on pregnancy outcomes while developing visual prediction tools like nomogram models to assist clinicians in formulating personalized embryo transfer protocols [9]. This model is expected to provide scientific support for optimizing embryo transfer timing and selecting optimal embryo types, thereby improving clinical pregnancy and live birth rates in SET cycles. Furthermore, the model's development will offer new insights and methodologies for future clinical research in assisted reproductive technology, promoting further refinement and advancement of pregnancy outcome prediction models.

## 2. Materials and methods

### 2.1. Study population

#### 2.1.1. Case source

The data for this study were obtained from the reproductive medicine center at Dongyang People's Hospital, covering thaw cycle SET cases and patient databases for assisted reproductive technology treatments from January 2021 to December 2025. Embryo transfer cycles involving SET during the thaw phase, derived from embryos fertilized via in vitro fertilization (IVF) or intracytoplasmic sperm injection (ICSI), were included in this study. Case selection adhered to criteria of data completeness and representativeness to ensure the included cases reflect the current real-world practice of SET [2]. After screening through the database, information from 1,131 eligible patients was extracted to form the core dataset for this study.

#### 2.1.2. Inclusion and exclusion criteria

To ensure the reliability of the study population and comparability of results, strict inclusion and exclusion criteria were established. The inclusion criteria were as follows: women aged 21 to 45 years old; undergoing thaw cycle SET; embryo developmental stages including Day 3 embryo transfer, Day 4 fused embryo, and Day 5/6 blastocyst transfer; and possession of complete clinical data, such as embryo quality assessment, endometrial thickness, and type. The exclusion criteria were as follows: history of uterine malformations, endometriosis, or adenomyosis affecting pregnancy outcomes; chromosomal abnormalities in either partner; and patients who had undergone more than three assisted reproductive treatments (i.e., beyond the third transfer cycle). After rigorous screening based on these criteria, 1,131 eligible cases were ultimately selected for analysis [2].

### 2.2. Data collection

#### 2.2.1. Patient baseline information

Patient baseline information constitutes a primary component of this study, encompassing female age, duration of infertility, baseline hormonal status (e.g., FSH, LH, and AMH), endometrial preparation method for the transfer cycle (including natural cycle, hormone replacement cycle, and low-dose stimulation cycle), and past pregnancy history. This information was obtained by reviewing electronic medical records and cross-verified by two independent researchers to ensure data accuracy. Age was recorded as a continuous variable and analyzed in groups based on interquartile ranges. The definition of duration of infertility is the time interval from the first attempt to conceive to the initiation of assisted reproductive technology treatment, and it should be recorded as a continuous variable. Additionally, past pregnancy history, including the number of natural pregnancies, miscarriages, and history of ectopic pregnancy, was obtained through detailed patient interviews and corroborated with medical records.

#### 2.2.2. Embryo-related data

Embryo-related data were collected in strict accordance with international standardized protocols. Day 3 embryo quality was assessed using a morphological scoring system, focusing on key indicators such as the number of blastomeres, uniformity, and fragmentation percentage. For Day 4 fused embryos, further documentation of fusion status was required, including partial fusion, complete fusion, and early blastocyst formation. These data were recorded by experienced embryologists based on microscopic observation and then verified against the data stored in the laboratory information system. For Day 5/6 blastocysts, the

Gardner scoring system was employed to grade expansion status, inner cell mass quality, and trophectoderm quality. All embryo-related data were collected before transfer to ensure timeliness and accuracy.

Additionally, parameters of the embryo culture environment were included in data collection, such as incubator temperature (37.0 ± 0.1℃), $CO_2$ concentration (5.0 ± 0.1%), and humidity (saturated humidity). All culture conditions strictly adhered to the ISO 15189 laboratory quality management system standards to ensure standardization of the embryo culture process. For frozen-thawed embryos, vitrification and rapid thawing methods were used, with documentation of post-thaw survival status (fully viable, partially viable, or non-viable) and morphological changes. The number of embryos transferred was determined based on clinical guidelines and patient preferences, recorded as a single transfer, with annotation of the specific developmental stage of the transferred embryo (Day 3 cleavage-stage embryo, Day 4 fused embryo, or Day 5/6 blastocyst). All embryo-related data were entered into the laboratory information management system (LIMS) in a structured format, with data entry permissions and automatic validation rules established to prevent manual entry errors. Monthly internal cross-comparisons of embryo morphological scores were conducted to ensure consistency among embryologists, and annual participation in at least one national-level embryo morphological quality assessment program validated the accuracy and reliability of the scoring standards.

### 2.2.3. Endometrial data

Measurements of endometrial thickness and type were performed via transvaginal ultrasound on the day of embryo transfer, the day of progesterone conversion, and the day before conversion. Endometrial thickness was defined as the maximum vertical distance between the anterior and posterior uterine wall muscular layers and the endometrial interface, with results recorded in millimeters. Endometrial types based on ultrasonographic echogenicity characteristics can be classified into three types: type A (triple-line sign), type B (homogeneous moderate echogenicity), and type C (hyperechogenicity) [4]. All measurements were independently performed by two experienced ultrasonographers, with the final result taken as the average of their measurements. Additionally, endometrial thickness measurements were timed on the day of luteal conversion or the day before transfer to minimize measurement errors [4].

## 2.3. Research methods

### 2.3.1. Statistical analysis methods

This study used SPSS 20.0 and R software (version 3.5.0) to perform statistical analyses. First, potential factors associated with pregnancy outcomes were selected based on univariate analysis, including patient age, duration of infertility, embryo development stage, endometrial thickness and type. Count data were presented as frequencies (percentages) and compared using the chi-square test or Fisher's exact test. For measurement data that were not normally distributed, results were expressed as median (interquartile range), and analyzed using the Mann-Whitney U test or the Kruskal-Wallis H test [9]. Variables that were statistically significant in the univariate analysis were then incorporated into a multivariate logistic regression model, and a stepwise backward LR method was applied to select the variables ultimately retained in the model. The discriminatory ability of the model was assessed using the receiver operating characteristic curve (ROC) and the area under the curve (AUC), while calibration was evaluated using the Hosmer-Lemeshow test.

### 2.3.2. Model construction methods

Based on the results of multivariate regression analysis, this study constructed a nomogram-based pregnancy outcome prediction tool. The nomogram model converts regression coefficients of independent factors into intuitive scoring scales, enabling clinicians to estimate pregnancy probabilities based on patient-specific conditions. The specific steps were as follows: first, determine the contribution weight of each factor to pregnancy outcomes and map it to the corresponding scoring axis; next, sum the scores of all factors to obtain a total score, then refer to the predicted pregnancy probability scale. This model was established using the rms package in R software and evaluated for stability and reliability through internal validation methods such as Bootstrap resampling [10]. The final nomogram model demonstrates high predictive accuracy and excellent clinical practical value, providing an important reference for personalized treatment decisions in SET patients.

## 3. Results

### 3.1. Patient baseline characteristics

This study included a total of 1,131 cases of single-embryo transfers. The age range of patients was from 23 to 45 years, with a median age of 32 years old (interquartile range: 28–37 years old). The primary causes of infertility were tubal factors (45.3%), male factors (27.8%), endometriosis (15.4%), and various other causes (11.5%). Based on the duration of infertility, most patients had infertility lasting between 2 and 8 years, with a median duration of 4 years (interquartile range: 2–6 years). Additionally, the distribution of pregnancy history among patients exhibited a skewed pattern, with 63.7% of patients having no prior pregnancies and 36.3% having had one or more pregnancies. Analysis of patient baseline characteristics revealed significant differences in age groups and causes of infertility across the overall sample, laying the groundwork for further investigation into the impact of these factors on pregnancy outcomes [3].

### 3.2. Embryo development and endometrial conditions

In terms of embryo development, the formation rate of fused embryos on Day 4 (D4) after Day 3 (D3) embryo transfer was 78.3%, while the formation rate of blastocysts on Day 5 (D5) or Day 6 (D6) was 65.7%. The distribution of embryo developmental stages indicated that D5 blastocysts accounted for the highest proportion (37.2%), followed by D6 blastocysts (28.5%) and D4 fused embryos (21.4%). Regarding endometrial data, on the day of embryo transfer, the mean endometrial thickness was 9.8 mm (interquartile range: 8.5–11.2 mm), with 84.6% of patients having an endometrial thickness greater than 8 mm. The endometrial types were primarily Type A (56.3%), Type B (32.1%), and Type C (11.6%), with Type A endometrium being significantly more prevalent than the other types. The findings suggest that embryo developmental stages and endometrial characteristics in this study exhibited diverse distribution patterns, and these variables may play a crucial role in pregnancy outcomes [4,5].

### 3.3. Univariate analysis results

Univariate analysis revealed significant correlations between patient age, embryo developmental stage, endometrial thickness and type, and pregnancy outcomes. Specifically, clinical pregnancy rates declined with increasing age, with patients aged 35 and above having significantly lower pregnancy rates than those under 35 ($p < 0.001$). In terms of embryo developmental stages, D5 blastocyst transfers yielded the highest

clinical pregnancy rate (64.63%), followed by D6 blastocysts (45.7%) and D4 fused embryos (38.6%), with statistically significant differences between groups ($p < 0.001$). Additionally, patients with endometrial thickness greater than 9 mm had significantly higher pregnancy rates than those with thickness less than 9 mm ($p = 0.002$); Type A endometrium also had significantly higher pregnancy rates than Types B and C ($p < 0.001$). These initial findings provide a basis for subsequent multivariate regression analysis.

In single-embryo transfer cycles, after controlling for age as a confounding factor, the impact of D3 cleavage-stage embryo scoring and blastocyst evaluation on pregnancy outcomes was as follows:

(1) Impact of D3 Cleavage-Stage Embryo Scoring

(a) Embryos were evaluated based on cell number, fragmentation rate, and symmetry according to ISCE criteria:

(b) Implantation: Embryos with 8 cells and a fragmentation rate <10% had a significantly higher implantation rate (48.2%) than those with 6 cells or a fragmentation rate >20% (29.5%, OR = 2.31, 95%CI 1.52-3.50).

(c) Miscarriage: High-quality D3 cleavage-stage embryos (8-10 cells, fragmentation rate <10%) had a 42% lower miscarriage rate (15.3%) compared to low-scoring embryos (26.4%, $P < 0.05$).

(d) Key Conclusion: D3 cleavage-stage embryos with 8-10 cells, a fragmentation rate <10%, and good symmetry had significantly better pregnancy outcomes than low-scoring embryos.

(2) Impact of Blastocyst Evaluation. Blastocysts were evaluated based on expansion status, inner cell mass quality, and trophectoderm morphology using the Gardner scoring system:

(a) Clinical Pregnancy: High-quality blastocysts (AA/AB grade) had a clinical pregnancy rate of 52.3%, significantly higher than non-high-quality blastocysts (BC/CB grade, 31.7%, $P<0.001$).

(b) Biochemical Pregnancy: High-quality blastocysts had a 43% lower biochemical pregnancy rate (64.3%) compared to non-high-quality blastocysts (21.3%, $P<0.01$).

(c) Live Birth Probability: AA-grade blastocysts had a live birth probability of 58.3% under favorable endometrial receptivity conditions, significantly higher than BC-grade blastocysts (OR=2.15, 95%CI 1.33-3.48).

(3) Comparative Analysis of Embryo Types (after controlling for age):

(a) Single blastocyst transfers had a clinical pregnancy rate and implantation rate of 64.53%, significantly higher than those of D3 cleavage-stage embryos (48.26%), with an absolute difference of approximately 16.5%.

(b) High-quality blastocysts (AA/AB grade) had better pregnancy outcomes than high-quality D3 cleavage-stage embryos; however, D3 cleavage-stage embryos meeting the criteria of 8 cells and a fragmentation rate < 10% still achieved a relatively good implantation rate of 48.2%.

## 3.4. Multivariate regression analysis results

Multivariate logistic regression analysis further identified independent factors affecting clinical pregnancy rates, including patient age, embryo developmental stage, endometrial thickness, and type. For each additional year of patient age, the odds ratio (OR) for clinical pregnancy decreased to 0.92 (95% confidence interval: 0.88–0.96, $p < 0.001$). In terms of embryo developmental stages, compared to D4 fused embryos, D5 blastocysts had an OR of 1.56 for clinical pregnancy (95%CI: 1.23-1.98, $p < 0.001$), while D6 blastocysts had an OR of 1.32 (95%CI: 1.05–1.66, p = 0.017). For each additional millimeter of endometrial thickness,

the OR for clinical pregnancy increased by 1.15 (95%CI: 1.08–1.23, $p < 0.001$). Additionally, compared to Type C endometrium, Type A endometrium had an OR of 1.84 for clinical pregnancy (95%CI: 1.36–2.48, $p < 0.001$). These regression coefficients provide quantitative support for constructing a clinical pregnancy prediction model and reveal the relative importance of each factor on pregnancy outcomes.

## 3.5. Prediction model construction and validation

### 3.5.1. Model construction

Based on the results of multivariate regression analysis, this study utilized a nomogram model to establish a pregnancy outcome prediction model. This model considered patient age, developmental stages of D3 embryos and D5 or D6 blastocysts, endometrial thickness, and type as primary predictive variables. Each variable was assigned a corresponding score based on its regression coefficient, and individualized pregnancy probabilities were calculated based on the total score. For example, a 30-year-old patient transferring a D5 blastocyst with an endometrial thickness of 10 mm and Type A endometrium would have a predicted pregnancy probability of approximately 60%. The advantage of the nomogram model is its intuitive display of the overall impact of each factor on pregnancy outcomes and its facilitation of rapid evaluation by clinicians in practical work [3]. A model related to clinical pregnancy and birth rate was also established.

### 3.5.2. Model validation

To evaluate the predictive performance of the model, this study validated its discriminatory ability using the receiver operating characteristic (ROC) curve and the area under the curve (AUC), as well as assessed its calibration using the Hosmer-Lemeshow test. The results showed that the AUC of the model's ROC curve was 0.832 (95% confidence interval: 0.798–0.866, $p < 0.001$), indicating high discriminatory ability. Additionally, the Hosmer-Lemeshow test results demonstrated good calibration of the model ($\chi^2 = 7.23$, df = 8, $p = 0.518$), meaning a high degree of consistency between predicted probabilities and actual observed probabilities. These validation metrics sufficiently demonstrate the reliability and effectiveness of the prediction model in clinical applications.

# 4. Clinical significance

When performing single-embryo transfer, prioritizing the selection of high-quality blastocysts (AA/AB grade) can significantly enhance the likelihood of a successful pregnancy while reducing the risk of early pregnancy loss.

If D3 cleavage-stage embryos are chosen, preference should be given to transferring embryos with 8 cells and a fragmentation rate of less than 10% to optimize pregnancy outcomes.

Embryo quality and endometrial receptivity have a synergistic effect: high-quality embryos placed in a receptive endometrium (with a thickness of 8–12 mm and Type A) can further increase the live birth rate to 58.3%.

The aforementioned conclusions are based on stratified analyses that exclude age as a confounding factor, providing more precise reference evidence for embryo selection in single-embryo transfer.

# 5. Discussion

## 5.1. Analysis of research findings

This study included 1,131 cases of single embryo transfer (including data from both elective and non-elective single embryo transfers) and developed a predictive model for pregnancy outcomes that incorporates multiple factors, including patient age, day 3 embryo transfer status, day 5/day 6 blastocyst development, endometrial thickness, and type. Due to the small number of day 4 transfer cycles, they were not included in the subgroup statistical analysis. The findings indicate that patient age is one of the primary factors influencing pregnancy outcomes, which is consistent with previously published literature [8,11]. Age-stratified analysis revealed that the clinical pregnancy rate in patients under 35 years of age was significantly higher than that in patients aged 35 years or older, with a similar trend observed for live birth rate, aligning with the findings of Huang Ya et al. [11]. Furthermore, blastocyst quality and developmental speed also significantly affect pregnancy outcomes; notably, in younger patient populations, the live birth rate following day 5 blastocyst transfer was significantly higher than that following day 6 blastocyst transfer, further confirming the importance of blastocyst developmental speed on pregnancy outcomes [12].

Analysis of endometrial characteristics revealed a significant correlation between endometrial thickness and pregnancy outcomes. Clinical pregnancy rates were significantly higher when endometrial thickness ranged from 8 to 12 mm, a finding consistent with existing literature [4]. However, the influence of endometrial type on pregnancy outcomes was not clearly established, which may be attributable to the relatively broad classification criteria for endometrial type used in this study. Of note, this study also found that the multiple pregnancy rate in the single cleavage embryo or blastocyst transfer group was significantly lower than that in the double embryo transfer group, a finding consistent with reference [1], further highlighting the advantage of elective single embryo transfer in reducing the risk of multiple pregnancy.

Compared with existing research, the predictive model developed in this study demonstrates certain innovations in terms of the comprehensiveness of included factors and the depth of data analysis. For example, in addition to considering patient age and blastocyst quality, the model also incorporates endometrial thickness and type, providing a more comprehensive reflection of the key factors influencing pregnancy outcomes. Moreover, the identification of independent influencing factors through multivariate regression analysis further enhances the predictive accuracy of the model [13].

## 5.2. Advantages and limitations of the model

This predictive model for pregnancy outcomes developed in this study has several notable advantages. First, the model integrates multiple factors, including patient age, embryonic development stage, and endometrial characteristics, enabling a more comprehensive assessment of the patient's reproductive capacity. Second, the use of a nomogram model provides a visual tool that allows clinicians to perform individualized predictions based on each patient's specific condition, thereby offering scientific support for embryo transfer decisions [14]. Furthermore, validation of the model's discrimination and calibration indicates high predictive accuracy, providing reliable references for clinical practice [9].

However, this study also has some limitations. First, the sample size is relatively small, including only 1,131 cases of single embryo transfer, which may limit the model's generalizability. Second, data were collected from a single reproductive medicine center, potentially introducing regional or institution-specific biases that may affect the model's general applicability to some extent [9]. Additionally, the classification

criteria for some variables are relatively broad; for example, the categorization of endometrial types lacks detail, which may reduce the model's ability to capture specific factors [4]. Finally, due to the retrospective study design, information bias may exist during data collection, which could also affect the accuracy of the model [9].

### 5.3. Guidance for clinical practice

The predictive model for pregnancy outcomes established in this study holds significant guiding value in clinical practice. First, this model can assist clinicians in more accurately assessing patients' reproductive potential, thereby facilitating the development of personalized treatment plans. For example, for patients of advanced age or with insufficient endometrial thickness, adjusting the timing of embryo transfer or optimizing endometrial preparation protocols can increase the likelihood of successful pregnancy [15]. Second, the model emphasizes blastocyst quality and developmental speed, providing scientific support for embryo selection. Particularly in single embryo transfer strategies, prioritizing high-quality, rapidly developing blastocysts not only improves the chances of pregnancy but also effectively reduces the risk of multiple gestations.

Moreover, this model serves as an effective tool for communication between clinicians and patients. Based on the nomogram model, patients can intuitively understand their probability of pregnancy, thereby gaining an understanding of the risks and benefits associated with the treatment process. Such transparent information delivery enhances patient trust and compliance, ultimately improving overall treatment outcomes. Finally, the establishment of this model guides future advancements in assisted reproductive technology. For instance, incorporating more influencing factors or expanding the sample size could further enhance the model's predictive performance, thereby better serving clinical applications.

## 6. Conclusion

This study successfully developed a predictive model for pregnancy outcomes based on 1,131 cases of single embryo transfer, comprehensively considering multiple factors, including patient age, the developmental status of D3 embryos and D5/D6 blastocysts, as well as endometrial thickness and type. Univariate analysis and multivariate regression analysis were used to determine the independent effects of each factor on pregnancy outcomes, and a nomogram model was constructed to enable intuitive prediction of pregnancy probability. Model validation results demonstrated that the model has good discriminatory ability and calibration, providing a reliable basis for clinical decision-making.

The main value of this predictive model lies in its ability not only to improve the accuracy of pregnancy outcome predictions for single embryo transfer but also to offer clinicians a quantitative reference. For instance, when formulating individualized transfer strategies, clinicians can use the model to assess pregnancy probabilities under different embryo developmental stages and endometrial conditions, thereby selecting the optimal timing for transfer and the most suitable embryo type. Furthermore, the comprehensiveness and practicality of this model give it broad application prospects in the field of assisted reproductive technology, helping to optimize resource allocation, reduce the risk of multiple pregnancies, and improve overall treatment efficacy.

However, this study has certain limitations. First, the sample data were derived from a single reproductive medicine center, which may introduce biases related to regional characteristics and

specific population features. Future multicenter, large-sample studies are needed to further validate the generalizability of the model. Second, although the model incorporated several important factors, to minimize the impact of ovulation induction medications and high estrogen levels on pregnancy outcomes, only data from frozen-thawed single embryo transfer cycles were analyzed. Other variables that may influence pregnancy outcomes, such as the patient's metabolic status, immunological factors, ovulation induction protocols, and embryo fertilization methods, were not fully considered. Third, embryo quality assessment did not include time-lapse culture data; the model was established based solely on D3 embryo evaluations across all single embryo transfer cycles. Modeling criteria based on blastocyst assessment might offer better predictive capability. Therefore, future research should focus on exploring additional relevant factors to further refine this predictive model.

In addition, with the rapid development of artificial intelligence and machine learning technologies, the potential applications of these emerging tools in medical predictive models are becoming increasingly evident. Future studies could attempt to introduce machine learning algorithms into the field of pregnancy outcome prediction, using more complex model frameworks to uncover nonlinear relationships within the data and thereby further improve predictive performance. Interdisciplinary collaboration may also bring new opportunities for development in this area, such as analyzing embryo gene expression data through bioinformatics approaches to gain a more comprehensive understanding of embryo developmental potential.

In summary, the pregnancy outcome prediction model established in this study provides a key scientific tool for clinical practice in frozen-thawed single embryo transfer, though continuous improvement and refinement through subsequent research are necessary. It is hoped that future studies will achieve breakthroughs in expanding sample sizes, incorporating additional influencing factors, and adopting advanced technologies, thereby contributing more significantly to the advancement of precision medicine in assisted reproductive technology.

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## Disclosure statement

The authors declare no conflict of interest.

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