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Review Article

Embryo Assessment and Selection in Assisted Reproduction: A Review of Current Technologies and Clinical Evidence

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Abstract

Embryo evaluation and selection are the most important contributors to outcomes in assisted reproductive technology. The objective of this review is to provide a cumulative description of recent technologies for embryo assessment and selection in assisted reproductive treatment including their scientific background, clinical evidence, strengths and weaknesses. A detailed narrative review was performed using the PubMed, Scopus and Web of Science databases. Articles that had a focus on conventional morphology, time-lapse imaging and/or morphokinetic analysis or pre-implantation genetic testing or non-invasive embryo assessment techniques including those based on artificial intelligence pathways were selected if they were peer-reviewed studies. Clinical outcomes were focused on implantation, clinical pregnancy, live birth, and miscarriage rates. Conventional morphology still plays an essential role in daily practice, however its power to predict chromosomal competence and live birth is limited. Time-lapse imaging enhances monitoring development and standardization, yet it is not entirely clear if it leads to routine improvement of live birth rates. The clinical applications of pre-implantation genetic testing for monogenic disorders and pre-implantation genetic testing for structural rearrangements are well defined, although that of preimplantation genetic testing for aneuploidy is more patient-specific and it has not been without controversies. Non-invasive molecular techniques assisted by artificial intelligence embryo selection systems show promising predictive capacity, but they are not yet prospectively and multicenter validated for universal clinical use. Combining traditional assessment with genotype, test and AI applications, applied selectively on the basis of solid clinical evidence, established outcome reporting and ethical oversight is therefore the most balanced approach to enhancing reproductive performance in assisted reproductive treatment.

Keywords: Embryo Selection, In Vitro Fertilization, Preimplantation Genetic Testing, Time-lapse Imaging, Artificial Intelligence.

Introduction

Infertility affects a great deal of the reproductive population worldwide, and is a significant public health issue associated with severe psychological, social and economic problems (1). Since their development, assisted reproductive treatment (ART) and specifically in vitro fertilization (IVF), have revolutionized the management of infertility and resulted in millions of live births worldwide. However, in spite of the progress achieved in ovarian stimulation regimens and embryo culture conditions, as well as with cryopreservation protocols, IVF success is still far from perfect (2).

Embryo morphology and selection are among the most important determinants of treatment success in IVF regarding the proportion of implanted, clinically pregnant, and live birth (3). Purely static morphological assessment at defined developmental stages has taken precedence in selecting embryos historically (4). The conventional grading techniques such as cleavage-stage and blastocyst morphology scoring are easy to use and inexpensive and underlie the routine use in the clinic. However, morphological examination cannot be objective and it only gives limited data about the genetic integrity and developmental potential of the embryo (5). These in combination with inconsistencies between and within observers and poor associations between morphology and chromosomal status have caused concern on the predictive ability of conventional assessment (6).

Correspondingly, failure in implantation, miscarriage and recurrence IVF procedures are still caused by inefficient embryo selection (7). To address these shortcomings, a number of emerging technologies have been established with the potential of enhancing the objective of observation and value to forecast embryo developmental potential. Time lapse systems of imaging enable real-time monitoring of embryo development and extraction of morphokinetic values that can be associated with implantation potential (8). Simultaneously, preimplantation genetic testing (PGT) can be adopted to identify chromosomal imbalances prior to embryo transfer but its clinical application particularly in unselected groups of patients remains controversial, PGT is now a significant add-on to embryo selection in assisted reproductive technology. PGT consists of a number of specific applications which are, PGT-M (preimplantation genetic testing monogenic disorders), PGT-SR (preimplantation genetic testing structural chromosomal rearrangements), and PGT-A (preimplantation genetic testing aneuploidy). PGT-M and PGT-SR are normally used in conditions in which couples are known to have genetic mutations or chromosomal rearrangements, and their clinical roles in preventing the inheritance of genetic disorders are generally accepted (9).

Alternatively, non-invasive techniques have received increased attention recently; these include metabolomic analysis and cell-free DNA analysis of spent culture media (10,11). Also, the artificial intelligence (AI) and artificial machine learning paradigms have demonstrated their potential as a method of assisting embryo selection that offers automated processing of imaging data and predictive modeling with the potential to be superior to traditional methods that rely on the embryologist (12).

AI systems aim to reduce bias, use large datasets, however, issues related to the absence of transparency, external validation and applicability to clinical practice have constrained their overall acceptability (13). Considering the rapid coping rate of modern technological advancement and the growing body of clinical evidence, a careful evaluation concerning the existing embryo assessment procedures and ranking methods is required. The objective of this review is to provide an overview of the various technologies and their clinical performance with respect to reproductive outcome, limitations, and ethics.

Materials & Methods

Study Design

This review was carried out as a narrative literature review with the intention of summarizing and critically analyzing the existing technologies that are employed in the assessment and selection of the embryo when it comes to assisted reproductive technology. The critique concentrates on the classical and innovative methods, such as morphological analysis, time-lapse imaging, preimplantation genetic testing, and artificial intelligence-powered embryo examination models.

Search strategy

A comprehensive literature search was performed across several major scientific databases to identify relevant studies. The databases included PubMed/MEDLINE, Scopus, Web of Science, Google Scholar, The search was conducted to identify studies published between 2000 and 2025. The search strategy combined multiple keywords related to embryo assessment and assisted reproduction. The following keywords and combinations were used "embryo assessment", "embryo selection", "assisted reproductive technology", "in vitro fertilization", "time-lapse imaging", "morphokinetic analysis", "preimplantation genetic testing", "artificial intelligence in IVF", "AI-based embryo selection", boolean operators such as AND and OR were used to refine the search strategy and retrieve relevant literature.

Inclusion criteria for studies were included in the review if they met the following criteria:

- Published in peer-reviewed scientific journals
- Written in English
- Focused on embryo assessment or embryo selection techniques
- Investigated technologies used in assisted reproductive technology or in vitro fertilization
- Included clinical studies, systematic reviews, meta-analyses, or experimental research.

Exclusion criteria for studies were excluded if they:

- Were conference abstracts without full text
- Were case reports or opinion articles
- Focused on animal models without clinical relevance
- Did not directly address embryo assessment or selection methods.

Study selection process

The literature selection process was conducted in several stages. First, titles and abstracts of retrieved studies were screened to identify potentially relevant articles. Duplicate records were removed. Subsequently, the full texts of the remaining articles were assessed for eligibility based on the predefined inclusion and exclusion criteria. Only studies that directly addressed technologies related to embryo assessment and embryo selection were included in the final analysis.

Data extraction

Relevant data were extracted from the selected studies using a structured data extraction approach to ensure consistency. The following information was collected from each study:

- Author and year of publication.
- Study design.
- Type of embryo assessment technique.
- Study population and sample size.
- Main outcomes (implantation rate, clinical pregnancy rate, live birth rate).
- Key findings and conclusions.

This information was used to compare the effectiveness, advantages, and limitations of different embryo assessment methods.

Results:

To enable comparison of the various technologies of embryo assessment, the clinical outcomes of the various studies chosen are summarized in Table 1. The table shows the implantation rates, clinical pregnancy rates, live birth rates and miscarriage rates of various embryo selection methods such as time-lapse imaging, preimplantation genetic testing, and artificial intelligence-based systems.

Table 1: Clinical outcomes of embryo assessment technologies in assisted reproductive technology

Author year	**Study design**	**Embryo assessment method**	**Implantation rate**	**Clinical pregnancy rate**	**Live birth rate**	**Miscarriage rate**	**Key finding**
Meseguer et al., 2012	Prospective study	Time-lapse morphokinetic analysis	NR	SI: 44.9%, TMS: 53.9%	NR	NR	TMS increased the relative probability of clinical pregnancy by 20.1% per oocyte retrieval and 15.7% per embryo transfer (14).
Conaghan et al., 2013	Multicenter study	Time-lapse imaging	NR	NR	NR	NR	Eeva improved the prediction of usable blastocyst formation; specificity increased to 84.7% vs 52.1% with morphology alone (15).
Rubio et al., 2014	Randomized clinical trial	Time-lapse selection	44.9%	61.6%	51.4%	16.6%	Time-lapse improved implantation rates (16).

Goodman et al., 2016	Prospective randomized controlled trial	Time-lapse morphokinetic monitoring vs conventional embryo selection	51.0%	68.1%	NR	2.5%	The addition of morphokinetic parameters showed higher pregnancy and implantation rates, but the differences were not statistically significant compared with conventional selection (17).
Barrie et al., 2017	Retrospective observational study	Time-lapse embryo selection algorithms (six ESAs)	39.7%	NR	NR	NR	Existing morphokinetic algorithms showed low predictive accuracy (AUC 0.543–0.629), suggesting the need for clinic-specific embryo selection models (18).
Chen et al., 2017	Systematic review:	Time-lapse embryo monitoring vs conventional incubation	NR	RR 1.09 (95% CI 1.00–1.19)	RR 1.23 (95% CI 1.06–1.44)	RR 1.27 (95% CI 0.58–2.80)	Meta-analysis of 10 RCTs found insufficient evidence that time-lapse imaging improves IVF clinical outcomes compared with conventional methods (19).
Forman et al., 2012	Retrospective comparative study	Single embryo transfer with comprehensive chromosome screening	NR	68.6%	55.0%	10.5%	Genetic screening reduced miscarriage (20).
Scott et al., 2013	Retrospective comparative study	Blastocyst biopsy with comprehensive chromosome screening (CCS) using qPCR	79.8%	93.1%	84.7%	NR	CCS significantly increased implantation and delivery rates compared with routine embryo selection (21).

VerMilyea et al., 2014	Multi-center retrospective AI study	Deep learning model (Life Whisperer) using Day-5 blastocyst images	NR	Prediction sensitivity 70.1%	NR	NR	An AI model improved embryo viability prediction accuracy by 24.7% compared with embryologists (22).
Tran et al., 2019	Multi-center retrospective deep learning study	IVY deep learning model using time-lapse embryo videos	NR	Prediction performance AUC = 0.93 (95% CI 0.92–0.94)	NR	NR	A deep learning model accurately predicted fetal heart rate in pregnancy from time-lapse embryo videos across multiple IVF laboratories (23).
Zhang et al., 2022	Multi-centre single-blinded randomized controlled trial	Time-lapse incubator (Geri) versus standard incubator with static assessment	First transfer: 52.35% vs 47.11% (P=0.014); adjusted RR 1.11, 95% CI 1.02–1.20, P=0.020. Cumulative: 50.69% vs 48.09% (NS)	NR	First transfer LBR: 63.24% vs 61.60% (NS). Cumulative LBR: 78.59% vs 78.76% (NS)	NR	Time-lapse significantly improved implantation rate in the first embryo transfer cycle, but did not significantly improve cumulative implantation or live birth rates (24).
Kaser & Racowsky, 2014	Systematic review	Time-lapse monitoring for embryo selection compared with conventional morphology	NR	NR	NR	NR	Evidence was sparse, heterogeneous, and insufficient to support routine clinical use of TLM for embryo selection; TLM should remain experimental until stronger prospective data are available (25).
Giménez et al., 2023	Clinical observational study	Morphokinetic embryo assessment	NR	NR	NR	NR	TLI is a promising non-invasive tool for embryo assessment, and many morphokinetic markers

							have been associated with blastocyst formation, implantation, pregnancy, live birth, and ploidy; however, its direct clinical benefit remains debated (26).
Bhide et al., 2024	Large randomized trial	Time-lapse imaging systems	NR	40.9%-43.4%	33–36%	8.7%	No significant improvement in live birth (27).
Illingworth et al., 2024	Randomized double-masked trial	Deep learning (iDAScore) vs morphology	NR	46.5% vs 48.2%	39.8% vs 43.5%	NR	AI comparable or superior to manual grading (28).

Traditional embryo assessment still serves as the basis of daily practice for the selection of embryos in ART laboratories across the globe. This method mostly relies on morphological observation of embryos at pre-determined developmental stages by light microscopy (29). Despite sophisticated assessment techniques that have appeared in recent years, morphology-based selection is still commonplace because of its simplicity, inexpensiveness and longstanding clinical familiarity (30). Cleavage-stage embryo evaluation is usually done on day 2 or 3 post-fertilization. Evaluation is based on the number and symmetry of blastomeres, amount of cytoplasmic fragmentation, presence of multinucleation and their scatter among other cell characteristics (31). The embryos with suitable number of equally sized blastomeres and little fragmentation are thought to have better developmental competence in general (32). The cleavage-stage morphology represents only a small part of embryonic development and has been poorly correlated with chromosomal normality and implantation potential. It has been shown that embryos with optimal cleavage stage morphology can still contain aneuploidies, thus resulting in implantation failure and/or early pregnancy loss (33).

Blastocyst stage (day 5 or 6) evaluation is regarded as being more informative than cleavage-stage assessment since it represents sustained developmental capacity of the embryo (34). The most popular is the Gardner and Schoolcraft grading system based on an evaluation of blastocyst expansion, inner cell mass (ICM) quality, and trophectoderm (TE) morphology (35). Transfer of blastocyst has been linked with better implantation and live births rates than cleavage stage. Notably, high-ICM and TE grades have been associated with positive clinical findings (36). However, even in morphologically high-grade blastocysts, a high percentage could be chromosomally abnormal and hence predictive value of morphology alone limited (37).

Conventional embryo evaluation is severely limited by its subjective nature. The morphological grading is subjective being highly influenced by the experience and perception of the embryologist that causes significant inter- and intra-observer variation. Variation in laboratory procedures, timing of evaluation and grading thresholds also results in a lack of consistent ranking of embryos between centers (38). This subjective decision-making decrease the reproducibility and confine the standardization of embryo selection, especially in multicenter studies and clinical trials. As a result, the dependence on morphology alone could lead to biased clinical decision-making and the therapy efficacy (39).

Although the traditional morphology-based assessment is helpful in excluding embryo with obviously poor development potential, it is of limited value to predict implantation and live births and neonatal status. Meta-analyses have demonstrated that morphology alone is unable to reliably differentiate between euploid and aneuploid embryos or fully predict embryo-endometrium crosstalk (40).

These drawbacks have prompted the emergence of adjunctive techniques of embryo selection, including time-lapse imaging, genetic testing and non-invasive evaluation of biomarkers, as mechanisms to enhance objectivity and predictability in embryo selection. Despite the fact that it is limited, traditional embryo assessment is part of ART practice. It provides a quick, non-invasive preliminary screening tool and a foundation upon which more advanced selection procedure tend to be based upon. In the majority of IVF programs especially those that do not have advanced instrumentation, ET decisions are still made on the basis of morphology (41).

Time-lapse imaging and morphokinetic analysis

Recently, time-lapse imaging (TLI) has emerged as a new method of embryo assessment as a solution to the limitations of fixed morphological analysis. TLI provides dynamic data on the timing of development and cellular activities that cannot be visualized with traditional observation because it can provide long- term, non-invasive, continual monitoring of embryo development under controlled culture conditions. Time-lapse systems are the incubators that are used along with automated microscopy and image software that allow embryos to be observed at specific times without being taken out of optimal culture conditions. It is akin to the technique of reducing changes in temperature, pH and gases concentration known to affect embryo development. Repetitive image acquisition provides highly resolved developmental time lines, allowing an accurate temporal description of crucial embryonic landmarks from fertilisation until the formation of the blastocyst (42).

Morphokinetic analysis is the assessment of timing and sequences of embryonic developmental events observed with the use of time-lapse imaging. Among the various parameters measured, time of pronuclear fading, 2-cell, 4-cell, and 8-cell stages were commonly evaluated together with synchrony and timing of blastomere division. Certain irregular events including direct cleavage and multinucleation can be more accurately detected by TLI (26).

Some researchers have reported that embryos with normal morphokinetic evolution are prone to implant and achieve clinical pregnancy. As a result, numerous morphokinetic algorithms and scoring systems have been developed in order to

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prioritize embryos based on their predicted potential for implantation (43,44).

The clinical value of time-lapse imaging has been investigated extensively, predominantly in relation to enhancement of implantation, clinical pregnancy and ongoing live birth rates. Although some cohort studies reinforced the efficacy of TLI-assisted embryo selection, there were inconsistent experimental results in randomized controlled trials and meta-analyses (45). A review has reported that there is insufficient high-quality evidence to determine a clinically meaningful increase in livebirth rates when TLI is incorporated routinely rather than conventional morphology assessment (25). TLI seems to be useful as a tool for supporting the selection more than as an independent indicator, especially when combined with classical morphology or genetics. Time-lapse observation has several advantages compared with the conventional assessment. Real-time surveillance also leads to the detection of transient or abnormal developmental processes that can be missed otherwise. Handling fewer embryos may contribute to the laboratory stability and directly enrich embryo quality. Moreover, the quantitative time data generated by TLI may eliminate some of the subjective and inter-observer bias in embryo selection (46).

Artificial intelligence and machine learning in embryo selection

Artificial intelligence (AI) and machine learning (ML) have become the new possibilities of the practice of assisted reproductive technology, namely, in the field of embryo assessment and selection. Transparently, by enabling the complex, high-dimensional data to be analyzed automatically, AI-based systems aim to increase the objectivity, reliability and overall predictive strength of embryo selection beyond what could be achieved using conventional means alone. Molecular pathways of embryo development are complicated and dynamic, they require the dynamic combination of morphological, temporal, genetic and environmental factors. The conventional assessment techniques rely solely on the subjective interpretation and discrete parameters, thus limited in the prediction potential. The AI and ML techniques might possibly be applied to identify the discrete changes, non-linear relationships in complex data sets with the hope of determining more accurately or reproducibly, the rates of implantation and live births (47).

The embryo selection process has been carried out by use of different types of AI methods like machine learning, supervised, deep learning, and CNN model. An example of supervised learning algorithms is the one trained using annotated data, e.g., labeled trophectoderm cells with known clinical outcomes, but deep learning models can work with raw embryo images or time-lapse sequences without human guidance (48). CNN models have produced the most encouraging results in the case of analysis of stationary embryo images, time-lapse videos that provide automated scoring schemes of the embryos which then outperform embryologist performance in retrospective experiments (48). The AI-assisted embryo selection systems tend to incorporate data on multiple sources, including image of the static morphology, morphokinetic parameters obtained by time-lapse analysis, demographics and clinical cycle of the patient. Multimodal data integration has also been shown to enhance the performance of the model compared to its performance when using single modality at the cost of more complexity and size of high quality training and validation data. Several studies have demonstrated that AI-based models can be used to predict the outcome of implantation and pregnancy as reliably or more so than the prediction of model predictions given by trained embryologists. Nevertheless, the majority of the available data are retrospective assessments or one-centred cohorts. It has no external validation, prospective randomized trials and conclusive data that predictive accuracy increase results in an improvement in live birth rates (49).

Artificial intelligence systems, in turn, have several challenges in the form of such issues as algorithmic bias, interpretability and generalization. It may not be adequate to make adjustments to only single laboratories or cohorts of patients in order to make broad generalisation of the models to new clinical settings. Moreover, most deep learning models are black boxes, something that limits clinicians to interpret or have trust in such interpretations on the decision making decisions (50).

A review study states that there is also no standardized datasets and reporting framework, thus, it is hard to compare the performance of AI models across studies (51). The implementation of AI in embryo selection raises important ethical and regulatory issues like accountability over clinical decision making, rights to privacy on information and informed consent. Depending on the jurisdiction in question, the regulatory acceptance of AI-based medical devices is yet to be defined, and the demarcations regarding the clinical application of ART have not been delineated yet. Professional associations point out that AI may be utilized to support the decision making process rather than replace expert judgement explainable AI, multimodal biological data integration, and prospective validation through randomized controlled trials are possible future directions of the AI-based. The integration of AI and non-invasive biomarkers and genetics can possibly offer more personalized, supported-based methods of embryo selection translating into better clinical outcome, yet not without ethical and clinical standards (52).

Discussion

Embryo assessment and selection are still the key predictors of success in assisted reproductive technology (ART), and they directly affect the rates of implantation, clinical pregnancy, and live births. Despite the fact that traditional morphology-based embryo grading remains to be the backbone of embryo selection when it comes to clinical practice, its predictive power is rather insufficient because of the subjectivity of the technique and poor association with chromosomal competence and implantation potential (4, 5,33). The mentioned limitations have inspired the creation of new embryo assessment technologies, such as time-lapse imaging (TLI), preimplantation genetic testing (PGT), non-invasive molecular techniques, and prediction models based on artificial intelligence (AI).

As indicated in the current review, although there is promise in emerging technologies in enhancing embryo assessment, the clinical implications of the technology on reproductive outcomes are inconsistent across studies. Morphological evaluation is still popular because it is simple, cost-effective, and has a long clinical history (29,30). But morphological grading is very subjective to an interpretation by the embryologists, and is connected with a significant inter and intra observer variability (38). Also the morphology per se is not reliable in identifying the types of euploid and aneuploid embryo or predicting potential of implantations (40). The dependence on morphology is therefore possible to cause implantation failure or unsuccessful IVF attempts (7).

Time-lapse imaging (TLI) is one of the most popular embryo evaluation innovations that have ever been studied. Time-lapse systems provide a continuous observation of the embryo development under stable culture conditions, which makes it possible to determine morphokinetic parameters that could be associated with embryo viability (42). Some of the studies incorporated in this review have indicated the enhancement of embryo selection with morphokinetic parameters obtained through time-lapse monitoring. To illustrate the point, Meseguer et al. showed that the incubation and selection of embryos under a time-lapse monitoring system was more probable to result in clinical pregnancy than in the usual incubator evaluation (14). Likewise, Rubio et al. also found considerable improvement of implantation, clinical and live birth rates among embryos that were chosen based on morphokinetic analysis in a randomized controlled trial (16).

The possible advantages of time-lapse imaging in the selection of embryos have also been demonstrated by other studies. According to Conaghan et al., the automated time-lapse image analysis enhanced the ability to predict the usable blastocyst formation with the help of morphology only (16). More so, observational research has also indicated that morphokinetic markers could be used to select embryos with enhanced development and chances of implantation (26).

These encouraging results notwithstanding, findings on time-lapse systems as a whole are not consistent in terms of clinical superiority. Goodman et al. discovered that the number of implantation and pregnancy rates were significantly greater when morphokinetic parameters were combined with embryo selection, although the differences were not significant as compared to conventional selection by morphology (17). On the same note, Barrie et al. observed that existing morphokinetic algorithms published in the past were found to have low predictive validity when used externally, and a clinic-specific embryo selection model is necessary (18).

The evidence of uncertainty about the clinical benefit of time lapse imaging has also been further emphasized by meta-analyses and systematic reviews. When Chen et al. analyzed randomized controlled trials to compare time-lapse systems with the traditional incubation of embryos, they did not find adequate data to prove the significant beneficial effect on reproductive outcomes (19). Similarly, the systematic review by Kaser and Racowsky found that the existing evidence is still diverse and not enough to justify the common clinical use of time-lapse monitoring of embryo in order to select the embryo (25). These results indicate that time-lapse imaging is a better method of monitoring embryos and offering quality data on development, but its capacity to consistently increase live birth rates is still under scrutiny.

New randomized trials can give more details to the clinical role of time-lapse systems. According to Zhang et al., the implantation rate of the embryos cultured and assessed in a time-lapse incubator was dramatically high in the first embryo transfer cycle in contrast to the control incubators. There were however no significant differences between the cumulative implantation rates and the cumulative live birth rates in the groups (24). On the same note, a multicenter randomized trial carried out by Bhide et al. showed no significant difference in live birth rates when embryo had been incubated and selected using a time-lapse system of imaging (27). These results imply that, although time-lapse imaging can be used to enhance embryo prioritization during early transfer cycles, there is no guarantee that it will enhance the overall reproductive capacity of the embryo cohort.

Another strategy that can be considered instrumental in enhancing embryo selection is the preimplantation genetic testing (PGT). PGT enables observation of the presence of chromosomal abnormality or inherited genetic disorders before embryo transfer, therefore minimizing the possibility of transfer of genetically defective embryos (47,48). The trials assessing overall screening of the chromosomes have showed better reproductive success as compared to the traditional embryo screening. In one example, Forman et al. found that the ongoing pregnancy rates and reduced miscarriage rates with single embryo transfer that was accompanied with extensive chromosome screening (20). On the same note, Scott et al. also concluded that the implantation and delivery rates were significantly higher with blastocyst biopsy with extensive chromosome screening than with standard embryo selection processes (21). However, the clinical efficacy of PGT, specifically PGT-A, is still debated in the context of unselective groups of patients. Although observational studies have been found to record better implantation rates and lower miscarriage rates, other randomized trials and meta-analyses have yielded opposing findings on live birth outcomes (54).

In addition to that, there are also technical issues of mosaicism, uncertainty in the diagnosis, and risks associated with the biopsy of the embryo which are significant drawbacks of the technique (51).

Artificial intelligence is a potential solution to embryo evaluation and selection in recent years. The implementation of AI-based models is based on machine learning and deep learning algorithms to give predictions on the possibility of implantation on the basis of embryo images or time-lapse measurements (47). A number of studies have produced promising predictive performance in the case of AI-based embryo assessment systems. As an example, VerMilyea et al. created a deep learning model, which can predict embryo viability using static images with additional accuracy compared to traditional embryologist evaluation (24). On the same note, Tran et al. indicated that a deep learning model that used time-lapse embryo videos could achieve high predictive accuracy on fetal heart pregnancy outcomes in various laboratories engaged in IVF (23).

Nonetheless, the clinical usefulness of AI-based embryo selection is still under research. A recent randomized double-blind study by Illingworth et al. compared AI-based embryo scoring with standard morphology-based selection and showed no difference in the pregnancy and live birth rates between the two methods (28). Such results indicate that, despite the potential to enhance the objectivity and decrease the subjectivity in the analysis of embryos, AI cannot prove its apparent superiority to the existing embryologist-based technique yet (53).

Other methods of non-invasive embryo assessment have also been receiving growing interest within the past few years. These methods also seek to assess the viability of embryos by analyzing metabolic biomarkers, proteomic biomarkers, or cell-free DNA biomarkers found in embryo culture media without having to biopsy embryos (48). Whereas preliminary findings have indicated a linkage between metabolic profiles and implantation potential, major differences between laboratories and methods of analysis have deterred clinical implementation (50). Equally, the preliminary studies on non-invasive preimplantation genetic testing of cell-free DNA have had encouraging outcomes, however, issues with maternal DNA contamination and the lack of diagnostic accuracy are still major obstacles to routine clinical practice (55).

The general conclusions of this review indicate that although a number of the current embryo evaluation technologies are advanced, none of them show its obvious and consistent advantages in enhancing live birth results. Both methods have their own pros and cons. Traditional morphology is still necessary to screen embryos at the start of their development, time-lapse imaging can be more useful to monitor development, genetic testing can be more effective to identify chromosomal abnormalities, and AI systems could enhance standardization and predictability.

Research that will be conducted in the future should integrate the various embryo assessment modalities instead of using one technology. Morphological analysis, morphokinetics, genetic identification, and AI-inspired predictive models could offer a more efficient and in-depth estimate of the developmental potential of embryo. Also, massive multicenter randomized controlled trials with standardized outcome reporting are necessary to establish the actual clinical worth of the new embryo assessment technologies.

Conclusion

Traditional morphology remains the clinical basis of embryo evaluation, providing a simple and widely accessible screening method. Although time lapse imaging improves the monitoring and standardization of development, when used in clinical practice it has not consistently shown a clear increase in live birth rates. The role of preimplantation genetic testing is well defined in specific clinical cases, involving single gene disease and structural chromosomal rearrangements, whereas the routine use of PGT-A is controversial and only reported to be beneficial in subgroups.

Non-invasive embryonic evaluation methods, as well as AI-based prediction models, are being developed because they may serve to increase objectivity and reduce the risk associated with various procedures used. However, these methods do not yet have the prospective, multicenter validation to support widespread clinical implementation. Standardization, interpretation and cost–benefit must be improve, as well as long-term safety for these techniques to become part of general clinical practice.

The evidence favors an embryo selection that is both context-dependent and patient-sensitive- the new technologies being selectively rather than ubiquitously deployed. Further progress will rely on robust prospective trials, uniformity of outcomes measurement, multilevel data adherence, and ongoing concern for ethical–legal–social issues. By integrating technology and strength of clinical evidence together with the patient perspective, embryo assessment can further evolve toward safer, more open, and thoughtful reproductive care.

Conflicts of interest: nil

Author contributions

All authors contributed to the collection of data, the preparation of the draft, and the review and approval of the final version of the manuscript.

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