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Review Article

Artificial intelligence in assisted reproduction: the future for reproductive medicine

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ABSTRACT

An important turning point in the development of assisted reproductive technologies has come with the use of artificial intelligence (AI). Because optimising results is such a constant struggle, AI is being used in assisted reproduction. This review presents a concise yet comprehensive overview of AI applications in ART, including its role in computer-assisted semen analysis (CASA), oocyte and embryo evaluation, personalized stimulation protocols, and treatment outcome prediction. AI augments objectivity, enhances prediction precision, and facilitates individualized therapy through the utilization of extensive, intricate datasets. Commercial AI platforms are increasingly integrated into routine IVF workflows, particularly in embryo grading and selection, showing promising preliminary outcomes. The need for openness and fairness in AI research, development, and implementation, as well as the identification of issues and moral quandaries surrounding AI support, are underscored by the lack of legislation addressing AI in healthcare. The goal of the regulatory framework is to strike a middle ground between worldwide innovation and patient safety. Highlighting possible benefits, limits, and ethical issues, this comprehensive research evaluates the advancement of AI in assisted reproduction.

Keywords: Machine learning, Deep learning, ICSI, IVF, Fertility

INTRODUCTION

Artificial intelligence (AI) is a scientific discipline dedicated to developing systems that generate outputs such as content, predictions, suggestions, or judgments aligned with human-specific objectives. This is achieved through computer neural networks composed of interconnected nodes, known as nodal points, capable of transferring data. This allows the machine to learn, develop, reason, process language, and resolve issues. There are two main areas of AI: machine learning (ML) and deep learning (DL). One of the main inspirations for DL came from the complex network structure found in the human brain. While many networks are capable of performing a wide variety of tasks, some are more suited to certain applications than others.[1]

Speech recognition, facial recognition, gaming AI, intelligent voice assistants, and self-driving cars are examples of AI applications that are used in daily life. Without a doubt, AI applications will advance in speed, intelligence, and usability. The current spectrum of AI applications is still fairly restricted though. Even with advancements, reaching universality remains a significant obstacle.[2-8] Improving success rates, increasing diagnostic precision, and resolving ethical controversies have long been obstacles for assisted reproductive technologies like intracytoplasmic sperm injection (ICSI) and *in vitro* fertilisation. Incorporating AI into assisted reproductive technology (ART) presents fresh solutions to long-standing problems. IVF, ICSI, and pre-implantation genetic testing (PGT) are all examples of assisted reproductive technologies that have changed the face of fertility care. These procedures are designed to help couples who are unable to conceive have a child by improving the chances of a successful implantation and allowing for external fertilisation.[9,10]

Progress in AI in ART mirrors that in AI generally across several domains. From early ideas to groundbreaking technologies, AI has come a long way and is now a powerful friend to mankind. ART is a difficult area that can benefit greatly from AI. AI's analytical powers make it possible to quickly and accurately analyse large databases, which in turn allows for individualised healthcare regimens that are specific to each patient.[11] With the help of AI, we can finally put an end to the long list of problems with assisted reproduction and usher in a new age of better, more individualised reproductive treatments.[12] An explanation of the many uses of AI in assisted reproduction is the goal of this narrative overview. The talk will go over the pros, cons, and moral questions raised by using AI for assisted reproduction. By shedding light on the topic, this study hopes to raise awareness among academics, practitioners, and stakeholders; this, in turn, should lead to better care in assisted reproduction, more ethical practices, and future innovations.

DEVELOPMENT OF AI IN ART

In the last two decades, the use of AI has become generalized from everyday tasks all the way to complex tasks such as use in ART. The ideology behind the implementation of AI in Health care systems was not undermine the clinical judgment of the clinicians but to give efficient decision-making opportunities as situations transition.[9] At present AI has become an irreplaceable part of digital clinical pathology and has become deeply rooted in multiple medical assessments ranging from medical imaging procedures all the way till partial clinical diagnostics.

AI has the ability to revolutionize ART by utilizing vast datasets to increase effectiveness and decrease subjectivity.[13] Although algorithmic bias and other ethical issues need to be addressed, AI applications in embryo selection, gamete evaluation, and customized treatment protocols seek to maximize results and expedite care.[14]

All be it, the exact place of AI in healthcare in general is a grey area shrouded in ethical considerations. AI has the potential to better improve the lives of the patients who are seeking treatment by providing specialized treatment plans based on the patient's medical history regarding previous stimulation cycles or allergies as well as provide a much wider perspective in pursuing a treatment than compared to clinicians input alone.

Even though we've come a long way since the first IVF baby, there are still many obstacles to overcome. Over 186 million people worldwide suffer from infertility, and the need for reproductive services is growing as a result of postponed childbirth and COVID-19-related disturbances that caused treatment delays during lockdowns.[15] High treatment costs, often exceeding $10,000 per IVF cycle, lengthy procedures, and variable success rates-ranging from 20-40% per cycle and plateaued over the past decade-limit access and efficacy.[16]

Repro-AI denotes a multidisciplinary technology that combines reproductive medicine with mathematical sciences to improve the utilisation of AI in the diagnosis and treatment of infertility. The effectiveness of repro-AI relies on continuous improvements and the application of automated time-lapse imaging, single-step culture, integration of digital and laboratory health data, and monitoring of environmental systems. Several of these technologies are on the verge of implementation, such as "laboratory on a chip" (IVF, ICSI, biopsy, and embryo cryopreservation in a microchamber) and "DIY" (do-it-yourself) IVF cycles.[17]

APPLICATIONS OF AI IN ART

Sperm assessment using AI

CASA

Computer assisted semen analysis is a computerized approach to assessing sperm characteristics such as motility, morphology, and concentration to name a few. This process of semen analysis provides more accurate as well as reproducible results than manual evaluation.[18]

CASA provides highly accurate and reliable data minimizing observer bias and enables standardized protocols across laboratories. However, for the accuracy of the data it is crucial that the sample should undergo standardized preparation, temperature control and proper calibration to avoid unnecessary artifacts in the image. Despite these criteria CASA remains a foundational and critical tool for evaluating sperm function and male infertility.

Automated analysis of sperm using AI

AI, particularly ML and DL algorithms, are being integrated into sperm analysis systems to improve accuracy, efficiency, and standardization beyond traditional CASA. AI models are programmed on large datasets of sperm images or videos to automatically classify sperm based on motility, morphology, and viability, reducing technician errors and improving diagnostic consistency.[19] These automated sperm analysis tools can far outperform the traditional CASA machinery by learning from the acquired data and consistently enhancing itself through model training.

However, their down side is that their clinical deployment required regular validation, standardization of inputs and regulatory approval, this ensures reliability and accuracy across diverse populations and laboratory environments.

AI in oocyte selection

In traditional oocyte selection subjective morphological assessment is used to select the best quality oocyte, the assessments being cumulus-oocyte complex appearance, zona pellucida thickness, cytoplasmic granularity, perivitelline debris. These assessments are limited by the embryologist's observation and poor predictive values for developmental competence.

AI DL models enables objective and automatic analysis of high-resolution oocyte images. These models can be programmed to recognize changes in the oocytes such as oocyte maturation, fertilization potential and embryo development outcomes which can be missed by the observing embryologist. Some approaches integrate time-lapse imaging, polar body morphology, or metabolic profiles with AI-based analysis to improve predictive performance.

AI in embryo grading

Traditional embryo grading relied on the manual observation of morphological criteria of the embryo such as the blastocyst expansion, inner cell mass and the trophectoderm quality. These observations however are subjective and can vary and have limited predictive value. AI has come about to automate as well as standardize the embryo assessment. AI especially DL techniques have been equipped or programmed with large datasets of embryonic images often obtained from time-lapse incubator images. These can detect subtle changes in visual features and temporal dynamics that can be dismissed by the embryologists.

These models provide an objective perspective in scoring embryos based on their implantation potential, often with higher accuracy as well as reproducible results than when compared to manual grading.

AI in personalized treatment plan

AI have become highly dependent upon whilst developing personalized treatment plans especially in the case of ART, AI aims to optimize the outcomes all the while reducing the error that comes about in clinical decision-making.

Traditional ART protocols rely mainly on population-based guidelines; however, they fail when considering inter individual variability in the case of ovarian response, embryo implantation potential or the risk for any severe complications.

ML models deploy analysis of large multidimensional data sets which takes in account the population demographic, hormonal profiles, ovarian reserve markers, stimulation history, genetic information as well as the treatment outcomes.

AI improves ovarian stimulation and shortens treatment cycles by optimizing medication selection and dosage based on patient-specific factors.[20,21] AI-optimized protocols reduced follicle-stimulating hormone (FSH) usage by up to 20%, potentially lowering medication costs.[22]

ADVANTAGES OF AI IN ART

Objectivity and standardization

The visual assessment of sperm, oocytes, and embryos by embryologists is a major component of traditional evaluation, which creates heterogeneity between and among observers. By more accurately and consistently detecting minute morphological traits, AI-driven image analysis tools-especially those that use DL-have shown that they can standardize grading.[24] Large annotated datasets are used to train AI systems, enabling the use of consistent criteria across many operators and clinics. Reproducibility is improved, and biases resulting from human fatigue, experience level, or cultural subjectivity in decision-making are also lessened.[25]

PREDICTIVE ACCURACY

AI models integrate clinical, hormonal, imaging, and historical outcome data to predict:

Ovarian response

With greater sensitivity and specificity than conventional models, AI algorithms can predict ovarian response by examining factors such as age, antral follicle count, hormone levels, and past stimulation history. These forecasts can help improve stimulation methods and customise gonadotropin dosage.[26]

Embryo implantation potential

ML models using time-lapse imaging, morphokinetics, and patient background data have shown promising results in forecasting implantation success, sometimes outperforming experienced embryologists in ranking embryo quality.[27]

Risk of treatment failure or complications (e.g., OHSS)

AI models can stratify the likelihood of adverse events like ovarian hyperstimulation syndrome (OHSS) and forecast cycle cancellation or bad results by incorporating patient-specific information (e.g., AMH, BMI, PCOS status, follicle counts), enabling preventative measures.

Improves selection of optimal treatment protocols, embryo quality, and timing

In order to offer personalised stimulation regimens that result in better outcomes with fewer medicines and cycles, ML models take advantage of patient-specific parameters such as age, ovarian reserve, hormone levels, and previous stimulation response. By identifying hidden patterns in extensive IVF data, a Chinese clinical AI system showed decision-level assistance and achieved noticeably higher predictive accuracy for cycle success and the best protocol selection.[28]

According to Table 1, AI systems like iDAScore, icONE, ERICA, and DeepEmbryo evaluate static and time-lapse embryo photos to rank and objectively evaluate embryo viability, eliminating subjectivity in hand grading. According to multicenter validation, icONE and iDAScore have an implantation prediction accuracy of 75-92%.[29]

AI algorithms find the best times for retrieval and transfer by continuously monitoring ovarian response and embryo growth. In addition to lowering workload and human error, integration with time-lapse incubators allows for dynamic, data-driven ranking.[27]

Table 1: Clinical application of AI in reproductive medicine.

Clinical application	AI predictive target	Model/tool/approach
Ovarian response	Suboptimal response in PCOS patients	Logistic regression +ML-based nomogram
Trigger timing (OPU)	Optimal trigger-to-OPU interval	ILTEA (AI enhanced DL+ GBT model)
Embryo viability	Implantation potential	iDAScore, static image DL models
Embryo selection	Embryo viability and implantation success	DL on blastocyst images (50,000+ dataset)
Embryo morphology-based prediction	Fetal heart pregnancy likelihood after blastocyst transfer	Time-lapse + CNN- based DL
Live birth prediction	Likelihood of live birth post embryo transfer	iDAScore vs. traditional morphokinetics
Risk stratification	Risk of early ovulation or poor outcome	Transformer Models + risk thresholds

PERSONALIZED MEDICINE

In order to develop predictive models for ovarian stimulation, treatment outcome, and embryo viability, AI systems incorporate a variety of patient-specific characteristics, such as age, BMI, AMH, AFC, hormone levels, and previous cycle response. Clinicians can use these tools to optimise individual-specific stimulation dosages and regimens.[30]

AI improves customisation by:

Optimised stimulation

Forecasting each person's ovarian reaction.

Accurate timing

AI algorithms predict when the trigger and oocytes will be picked up.

Embryo selection

AI uses clinical data, time-lapse imaging, and morphology to rate embryos according to their propensity for implantation.[31]

High-throughput analysis

Accelerates analysis in high-volume (busy) clinics (e.g., rapid assessment of sperm motility or embryo grading from time-lapse images):

AI accelerates routine tasks like sperm analysis and embryo grading:

Sperm analysis: AI systems (e.g., Mojo AISA, Olympus AI) reduce evaluation time from 30 minutes to under 5 minutes, with high accuracy and consistency.

Embryo grading: DL models (e.g., iDAScore, BELA) analyze time-lapse images in seconds, enabling automated, objective scoring.[32]

Increases laboratory efficiency all the while not compromising on accuracy:

When it comes to sperm identification and embryo evaluation, AI technologies outperform embryologists, decreasing inter-observer variability and boosting lab productivity.[32]

Non-invasive decision support

AI can evaluate embryos using non-invasive markers (e. g., time-lapse imaging, metabolomics) rather than requiring open or invasive biopsies:

Time-lapse imaging: DL models trained on tens of thousands of embryo videos (e.g. Attention branch network) can predict live birth outcomes using time-lapse images alone-without biopsy. Embryos above aa AI confidence score threshold had significantly higher live birth rates (41.1%) compared to lower-scoring embryos.[25]

Enhances embryo selection while preserving embryo integrity: AI models like iDAScore and DeepEmbryo, using time-lapse or static imaging only, matched or exceeded manual embryo grading consistency and effectiveness, avoiding biopsy-related embryo manipulation.[27]

Continuous learning and improvement

ML models show improved prediction ability when supplemented with new patient data, such as clinic-specific procedures, demographic changes, and population variations. Accuracy and therapeutic value are increased as a result of models' ability to adjust to variations in treatment responses among various patient populations thanks to ongoing learning.[33]

Resource optimization

Reduces unnecessary interventions and minimizes cycle cancellations. AI-driven tools help streamline ovarian stimulation and monitoring schedules by predicting the optimal point for clinical evaluation, AI models can also recommend optimal gonadotropin dosing and stimulation adjustments early, reducing overstimulation, medication use, and the risk of poor or excessive response.[13]

Significantly reduces the cost per live birth by improving first-cycle success rates.

Increased first-cycle live birth rates: AI-powered tools for gamete evaluation and embryo selection, such iDAScore and AI-driven selection platforms like AIVF's EMA, increase the likelihood of a live birth during the initial IVF attempt.

Reduced repeat cycles: Enhancing first-cycle performance lowers total expenses and eases the psychological and practical strain on patients and clinics.[34]

DISADVANTAGES OF AI IN ART

Lack of standardization

Variability in imaging protocols, laboratory practices, and data labeling across clinics limits the generalizability of AI models. Many models are trained on solely on clinic specific databases, severely reducing external validity.

"Black box" problem

DL models often lack interpretability, making it difficult to understand how decisions are made. The lack of transparency in the matter can hinder clinician trust and complicate regulatory approval.

Data quality and bias

AI is highly dependent on the quality, volume, and diversity of input data. Models trained on biased datasets (e.g., single ethnicity, specific equipment, or geographic region) may yield inaccurate or inequitable outcomes especially if the case population presented is not programmed into their database.

Limited regulatory oversight

Randomised controlled trials (RCTs) have not validated many AI systems in ART. Rather than thorough prospective trials evaluating AI against traditional therapy, the majority of the evidence is derived from observational or retrospective investigations. Although research based on simulations and retrospective analysis show potential, this reduces trust in their therapeutic impact and generalisability.[38]

Regulatory bodies like the FDA (USA), EMA (EU), and CDSCO (India) currently lack ART-specific guidance for AI applications. Existing frameworks treat such tools under general "software as a medical device" (SaMD) policies, which are not tailored to reproductive technologies.[35,36] The proposed EU AI Act and FDA's Good ML practice (GMLP) guidelines offer foundational principles but still leave critical gaps in lifecycle management, clinical validation, and patient safety specific to ART.[37]

Clinical integration challenges

Incorporating AI into clinical workflows requires significant investment in infrastructure, training, and interoperability with existing systems. The Lack of adaptability towards technology by the clinicians stemming from the lack of trust in technology.

ETHICAL AND LEGAL CONCERNS

Questions regarding liability in the event of AI-driven errors remain unresolved

It is still unclear who is legally liable for misdiagnosis or embryo mis-ranking caused by AI. Whether the doctor, clinic, software developer, or AI manufacturer is at fault in situations when AI-based suggestions lead to unfavourable results like failed implantation or embryo damage is not always obvious. The rules for medical malpractice that are in place now are not made to allow autonomous decision-support systems, particularly ones that use opaque algorithms.[39]

Use of personal reproductive data raises privacy and consent issues

Large-scale integration of sensitive personal data, such as genomic, hormonal, and imaging data from gametes and embryos, is frequently necessary for the application of AI in ART. This brings up important questions about informed consent and data privacy. Particularly when third-party AI suppliers are engaged, patients might not completely comprehend how their reproductive data will be handled, shared, or preserved.[39]

If in case of a breach in privacy, patient data could possibly get leaked

The necessity for standardized international standards that strike a compromise between patient safety and innovation is highlighted by the fact that present approval procedures are frequently unsuitable for continuously learning systems.[23]

Cost and accessibility

Even though AI has the potential to improve ART success rates and expedite procedures, putting advanced AI platforms into practice-like time-lapse incubators with built-in AI analysis or AI-based embryo selection systems-often necessitates a large initial outlay. Particularly in private or resource-constrained contexts where infrastructure and software subscriptions are costly, these technologies have the potential to increase the cost of therapy every cycle. People in lower socioeconomic classes or in low- and middle-income countries (LMICs) may find ART less cheap as a result of clinics passing these expenses on to their patients. By essentially establishing a two-tiered system-one with access to cutting-edge, AI-driven protocols and another depending on traditional techniques with varying success rates-this could exacerbate already-existing disparities in access to fertility care.[40]

CURRENT STATE OF AI IN ART

AI is reshaping the field of ART by introducing data-driven precision, standardization and is automating clinical and laboratory work. The current state of affairs show that AI is rapidly evolving from research-phase innovation towards early-stage clinical deployment all the while showing its application in embryo selection, gamete assessments and personalized treatment plans. DL systems have significantly improved precision and consistency in embryology as well as andrology. Research is advancing in AI-assisted oocyte assessment as well as developing personalized stimulation protocols.

Despite these advancements, clinical adoption of AI is constrained by many factors: lack of regulatory approval, “black box” problem dealing with transparency of the data and the need for extensive multicenter validation. Furthermore, integration of AI into daily clinical practice requires extensive investment into digital infrastructure and well as proper training for the following alongside dealing with the ethical concerns surrounding the use of AI.

In summary, while AI is not yet a universally adopted standard in ART, it is a fast-emerging tool with transformative potential. Ongoing developments are expected to refine and expand its role, ultimately moving the field toward personalized, evidence-based reproductive medicine.

FUTURE PROSPECT OF AI IN ART

Comprehensive decision-support systems

AI will evolve into integrated platforms capable of simultaneously analyzing patient history, hormonal profiles, genetic data, and gamete/embryo characteristics to provide holistic treatment recommendations.

These systems may guide protocol selection, dosage, embryo transfer timing, and cumulative live birth probability predictions in real time.

Multi-omics integration

Combining genomics, transcriptomics, metabolomics, and proteomics with AI will enable deep, non-invasive assessment of gamete and embryo viability, potentially replacing current morphology-based grading.

AI-driven automation

Full automation of ART laboratory processes (e. g., sperm sorting, oocyte ICSI selection, embryo monitoring) may become feasible, enhancing reproducibility and reducing manual error.

Robotics and AI may be integrated into micromanipulation procedures, minimizing operator variability.

Patient-centric personalization

Advanced AI models will enable dynamic treatment adaptation based on patient-specific response patterns observed during the cycle, improving efficacy while minimizing risks.

Federated learning and global data sharing

Secure, privacy-preserving AI models trained across institutions (federated learning) will overcome the limitations of isolated datasets, improve generalizability and reduce bias.

Improved transparency and explainability

Explainable models are being used more and more by contemporary AI systems in reproductive medicine to help physicians understand the reasoning behind decisions such as treatment protocol or embryo selection.

Certain patient characteristics (such as age, embryo morphology, and hormone levels) affected the prediction, as shown by tools like SHAP and LIME.

By making complex models easier to understand, this enhances transparency, fosters confidence in AI systems, and facilitates clinical decision-making.[41]

ETHICAL CONCERNS REGARDING AI

Data privacy and consent

AI systems rely on large volumes of sensitive personal and medical data, including images of embryos, hormonal profiles, and genetic information. Ensuring informed consent, data anonymization, and secure data storage is critical to protect patient confidentiality and comply with data protection regulations (e.g., HIPAA).

Bias and inequity

AI models trained on data from specific populations or equipment may perform poorly when employed elsewhere, potentially increasing existing disparities in reproductive care. There is a risk of algorithmic bias negatively impacting underrepresented groups, leading to unequal access or outcomes.

Autonomy and human oversight

Overreliance on AI may dull the clinician autonomy and reduce critical thinking, especially if systems are used without adequate human oversight. Patients must retain the right to make informed decisions, even when AI-derived recommendations are presented as optimal.

Regulatory and legal ambiguity

Unclear legal frameworks regarding liability in cases of AI-related errors or adverse outcomes complicate accountability. Determining responsibility when AI influences medical decisions remain a grey area in reproductive ethics.

Commercialization and exploitation

Proprietary AI platforms may prioritize profit over patient welfare, potentially leading to more harm than good. Ethical concerns also arise over the exploitation of embryos and gametes through algorithmic ranking.

CONCLUSION

AI is a fast-emerging transformative entity in the field of ART, employing diagnostic accuracy, treatment personalization and procedural efficiency. It provides an objective perspective, from embryo grading to individualized treatment and stimulation protocols.

However, despite these advancements the implementation of AI in ART faces key challenges such as algorithm transparency, data heterogeneity, ethical concerns as well as regulatory gaps. Future progress of AI will depend on large scale validation studies and cross institutional collaboration. In essence AI will not replace human judgement but will rather provide a "second opinion" when responsibly adopted.

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