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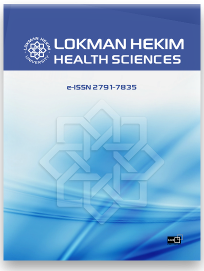
REVIEW



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Integrating Artificial Intelligence into Assisted Reproduction Technologies: Current Applications And Future Directions – A Narrative Review

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Abstract

In recent years, the integration of artificial intelligence (AI) into medicine has expanded rapidly, particularly within assisted reproductive technologies (ART) and *in vitro* fertilization (IVF). Traditional assessments in IVF—especially embryo morphology—are prone to subjectivity and may vary according to embryologist experience. AI-supported systems help overcome these limitations by enabling faster, more objective, and more consistent evaluation of clinical data and microscopic images. AI applications have been incorporated into multiple steps of the ART process, including oocyte and sperm assessment, fertilization analysis, embryo evaluation, ploidy prediction, and embryo selection for transfer. Beyond laboratory assessment, AI also contributes to micromanipulation, quality management, the processing of large datasets to support personalized treatment protocols, and improved genetic testing approaches. Collectively, these innovations enhance diagnostic accuracy, promote standardization, and increase treatment success rates in ART. This narrative review provides a comprehensive and up-to-date overview of AI applications within ART, with a particular focus on IVF laboratory processes, clinical decision-support tools, and related ethical considerations. A focused literature search was conducted in PubMed using the keywords "artificial intelligence" and "assisted reproduction." The search covered the period from January 1, 2020, to May 31, 2025, and included only English- and Turkish-language publications. Eligible studies consisted of meta-analyses, systematic reviews, narrative reviews, and original research evaluating the use of AI in human ART or IVF. Conference abstracts, editorials, expert opinions, letters to the editor, case reports lacking methodological clarity, non-human studies, and purely technical computer science papers without clinical relevance were excluded. Reference lists of the included articles were also examined to identify additional sources.

Keywords: Artificial intelligence; Assisted reproductive technologies; Individualized medicine; *in vitro* fertilization

Infertility is a disease of the male or female reproductive system and is defined as the failure to achieve pregnancy after 12 months or more of regular, unprotected sexual intercourse. Infertility may result from male, female, or unexplained factors.[1] Approximately 17% of people experience infertility at some point in their lives. Prevalence estimates are consistent across countries regardless of income level; 17.8% of individuals in high-income countries

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and 16.5% in low- and middle-income countries experience infertility. The prevention, diagnosis, and treatment of infertility remain underfunded and inaccessible for many individuals.[2] In Türkiye, the prevalence of infertility ranges between 10% and 20%, with 55–75% of these couples diagnosed with primary infertility and 25–40% with secondary infertility.[3]

The development of assisted reproductive technologies (ART) began in 1978 with the first successful *in vitro* fertilization (IVF), marking a groundbreaking milestone in the field. In the following years, alternative methods such as GIFT (Gamete Intrafallopian Transfer) and ZIFT (Zygote Intrafallopian Transfer) were introduced, expanding treatment options for infertility. In the 1990s, innovative techniques such as intracytoplasmic sperm injection (ICSI)—a revolutionary advancement particularly in the treatment of male infertility—and preimplantation genetic diagnosis (PGD), which enables screening of embryos for genetic disorders, were incorporated into clinical practice. During the 2000s, significant improvements in embryology laboratory techniques and cryopreservation methods—especially the widespread adoption of vitrification—led to substantial increases in success rates. In the following years, the effectiveness and scope of ART were further enhanced by the introduction of controlled ovarian hyperstimulation, luteal phase support, embryonic genetic testing, and oocyte cryopreservation. Today, novel approaches such as minimal stimulation protocols, GnRH agonist cycle triggers, and metabolomic/proteomic analyses continue to shape ART as an increasingly evolving and personalized field.

Conventional ART methods, such as *in vitro* fertilization and intracytoplasmic sperm injection, face several challenges that limit their effectiveness. These challenges include low success rates, high costs, invasive procedures, ethical concerns, a lack of personalized approaches, and the inherently subjective nature of both embryology and clinical practice. All these factors highlight the need for more standardized and technology-driven approaches to enhance the reliability and consistency of ART procedures.[4] Therefore, the aim of this narrative review is to provide a comprehensive and up-to-date synthesis of current artificial intelligence applications within assisted reproductive technologies, with a particular focus on IVF laboratory processes, clinical decision-support tools, and the associated ethical and regulatory considerations.

This narrative review was conducted using a structured literature search in the PubMed database. The search strategy combined the keywords "artificial intelligence" AND "assisted reproduction." The primary search covered publications from January 1, 2020, to May 31, 2025. Articles written in English or Turkish were included. Eligible publications comprised meta-analyses, systematic reviews, narrative reviews, and original research articles evaluating the use of artificial intelligence in human assisted reproductive technology or *in vitro* fertilization settings. Non-human studies, case reports lacking methodological clarity, editorials, expert opinions, letters to the editor, and purely technical computer science reports without clinical or laboratory relevance to assisted reproduction were excluded. Reference lists of the included publications were also screened to identify earlier seminal studies, relevant methodological studies, and selected preliminary reports that directly supported specific technical or laboratory statements. Because this was designed as a narrative review, no formal risk-of-bias assessment or meta-analysis was performed.

Clinical and Research Consequences

The Use of Artificial Intelligence in Assisted Reproductive Technologies

Today, artificial intelligence (AI) applications are widely used across various fields of medicine, offering significant advantages, particularly in areas such as medical imaging, personalized treatment planning, and robotic surgery. As a reflection of these advancements, the integration of AI-based approaches into the field of ART is bringing important innovations to reproductive medicine and gradually reshaping clinical and laboratory practices.[5]

This review provides a comprehensive overview of the integration of AI into ART, focusing on oocyte assessment and selection, sperm evaluation and selection, and embryo assessment and selection. It examines in detail the impact of AI on personalized treatment planning, diagnostic accuracy, ethical considerations, and the future of this rapidly evolving field.

Artificial Intelligence in the *in Vitro* Fertilization Laboratory

Manual procedures still dominate many steps of the *in vitro* fertilization laboratory. However, the integration of automation and AI has significant potential to reduce subjectivity in embryology, thereby increasing consistency and minimizing variability between embryologists.[6] In addition, AI-based sensors, processors, and integrated software systems enable real-time monitoring of key environmental parameters such as room temperature, humidity, volatile organic compounds, and door-opening frequency, and can initiate automated responses when deviations occur.[7] In IVF laboratories, AI-driven automation enhances workflow efficiency by performing continuous and objective assessments of gametes and embryos through time-lapse imaging platforms and deep-learning–based image analysis.[8] These algorithms automatically annotate morphokinetic events, detect fertilization patterns, track cell divisions, and flag potential errors in embryo identification, thereby reducing inter-observer variability and improving standardization.[8,9] Furthermore, AI-supported systems contribute to quality management by monitoring incubator conditions, equipment performance, and overall laboratory workflow, allowing early detection of deviations and reducing the risk of technical errors.[7,9]

Personalization of Ovarian Stimulation Protocols

The management of *in vitro* fertilization cycles depends on the ovarian response to treatment, which is evaluated during regular follow-ups to enable clinicians to make informed decisions and plan subsequent steps of the therapy. Selecting a personalized gonadotropin dose for oocyte stimulation is a complex process. Currently, the approach to determining the appropriate gonadotropin dose relies largely on the clinician's experience and the patient's response to previous treatment attempts.[10] During the ovarian stimulation phase, AI algorithms collect and process demographic characteristics, medical history, laboratory test results, medication dosages during treatment, and follicular ultrasound measurements to predict critical clinical decisions made by physicians, such as continuation of stimulation, timing of monitoring, dose adjustment, or cycle cancellation.

AI research on the selection of ovarian stimulation protocols remains limited, with only a small number of models developed to date.[6] Most published studies rely on retrospective, single-center datasets with heterogeneous samples, which restricts both reproducibility and generalizability.[11,12] In contrast to embryo assessment—where AI models have been trained on tens of thousands of images—AI-driven stimulation models are based on relatively small patient cohorts and lack external validation.[6,9] Moreover, no completed randomized controlled trials have yet demonstrated the clinical superiority of AI-guided protocols, underscoring the need for larger, prospectively designed studies before these tools can be routinely implemented in clinical decision-making.[6]

In the study by Correa et al.,[11] an AI model was developed to predict individualized starting doses of FSH for ovarian stimulation, using variables such as age, body mass index, anti-Müllerian hormone, antral follicle count, and previous live birth history. The performance scores obtained during the development and validation phases were found to be statistically significantly higher compared with the doses prescribed by clinicians. This AI-based approach not only supports the decision-making process and quality control monitoring but also has the potential to improve treatment efficiency by reducing the risk of cycle cancellation through personalized dose recommendations.

Fanton et al.[12] developed an AI algorithm based on the principle of patient similarity to optimize the selection of the initial FSH dose. The model generated personalized dose–response curves based on baseline parameters such as age, body mass index, basal AMH, and antral follicle count, thereby identifying the optimal dose range. Using this model, a higher number of fertilized embryos and usable blastocysts was obtained, while total FSH consumption was significantly reduced. These findings demonstrate the potential of AI-based dose recommendation systems to improve clinical outcomes and reduce costs.

Oocyte Assessment and Selection

The assessment of oocyte quality is a critical step in ART, as oocyte competence strongly influences subsequent embryo development and overall IVF success. Follicular volume correlates with the degree of ovarian response to stimulation and is widely recognized as an indirect marker of oocyte maturation.[13,14]

Because follicular size and volume serve as key maturation indicators, transvaginal ultrasound naturally becomes the primary method for monitoring follicular development during stimulation. Although two-dimensional ultrasound provides baseline measurements, three-dimensional ultrasound offers superior volumetric assessment and has been associated with improved planning for oocyte retrieval.[13] However, both 2D and 3D measurements remain highly operator-dependent, and variability can occur both between different clinicians and within repeated assessments by the same individual.[14] These limitations underscore the need for more objective and automated assessment tools in oocyte evaluation.

Recent advances in AI-based image analysis have made significant contributions in this area. Deep-learning models using transvaginal ultrasound datasets have enabled automated segmentation and quantification of ovaries and follicles, potentially reducing operator dependence in follicular monitoring.[6]

Targosz et al.[15] showed that deep neural networks can be used for semantic segmentation of human oocyte images, enabling automated identification of relevant morphological structures and supporting more standardized oocyte image analysis. Similarly, Firuzinia et al.[16] developed a robust deep-learning–based multiclass segmentation method for analyzing human metaphase II oocyte images, enabling automated evaluation of key morphological structures. These advances collectively demonstrate how AI-driven systems can strengthen objectivity and standardization in oocyte assessment.[6]

Timing of Trigger Injection

In ART, determining the optimal timing of the trigger injection is a complex decision-making process influenced by factors such as follicle size and hormonal indicators. However, AI, with its capacity to integrate multidimensional datasets, holds the potential to enhance the accuracy and precision of this decision-making step.[8]

In the study by Hariton et al.,[17] it was demonstrated that the use of machine learning algorithms to optimize the timing of the trigger injection in an IVF cycle could lead to a significant increase in both the number of fertilized oocytes and the total number of usable blastocysts compared with physician-determined decisions.

Letterie et al.[18] developed an AI-based algorithm aimed at predicting the optimal trigger day for oocyte retrieval during ovarian stimulation in the IVF process, using data from only a single monitoring day. The model was built upon pre-IVF clinical profiles, such as age, AMH level, and BMI, as well as estradiol levels, follicle count, and follicle diameters obtained from one day of the stimulation cycle. It was able to identify not only the ideal trigger day but also a three-day window—within a ±1 day tolerance—for oocyte retrieval. The model had a mean prediction error of 1.355 days and tended to estimate the trigger day earlier than the actual clinical decision, providing flexibility for additional clinical evaluation if needed. Furthermore, it was reported that shifting the trigger day forward or backward by one day resulted in an average variation of 0 to 3 in the total number of oocytes retrieved. This approach has the potential to enhance clinical efficiency.

Sperm Assessment and Selection

Male infertility is the primary cause in approximately half of all infertile couples.[19] In the context of IVF, sperm selection based on embryologist evaluation remains subjective, thereby contributing to interobserver variability.[20] Consequently, this underscores the need for objective and standardized methods in sperm assessment. To address this, Ottl et al.[21] developed an AI algorithm that facilitates the selection of the fastest sperm for fertilization by calculating head movement velocity. Similarly, Riordon et al.[22] demonstrated that an AI algorithm analyzing sperm head morphology surpassed traditional assessment methods, achieving an accuracy of 94.1%. Furthermore, Sato et al.[23] introduced an algorithm capable of both tracking sperm and evaluating them morphologically. In addition, Mendizabal-Ruiz et al.[24] introduced SiD software, which enables real-time single-sperm selection by computing motility parameters, including straight-line velocity and the linearity of the curvilinear path. Moreover, increased DNA fragmentation in sperm cells is known to negatively affect fertilization potential.[25] In response to this challenge, McCallum et al.[26] introduced an AI-based algorithm capable of predicting DNA fragmentation in sperm cells using bright-field images, further expanding the scope of objective and non-invasive sperm assessment.

Despite these promising technical results, the clinical implementation of AI-based sperm assessment tools remains challenging. Most available algorithms are developed using heterogeneous, single-center datasets and require extensive validation before routine use. In addition, high costs, the need for standardized imaging conditions, and the absence of universally accepted laboratory protocols currently limit the widespread adoption of these systems in daily andrology practice.

Fertilization Assessment

As the earliest measurable indicator of successful gamete interaction, fertilization assessment provides essential information for early embryo development and represents a key area in which AI may offer objective and clinically meaningful support.[6,8]

Dimitriadis et al.[9] developed an algorithm capable of distinguishing between normally and abnormally fertilized oocytes, achieving an accuracy of 93.1%.[27] These findings highlight the potential of AI in the assessment of fertilization. Although further research is needed, the use of AI in fertilization evaluation may contribute to higher pregnancy rates through more efficient embryo selection.

Embryo Assessment

Manual evaluation of embryo morphology is inherently subjective and demonstrates substantial intra- and interobserver variability.[28] AI-assisted image analysis reduces this variability by more precisely identifying subtle morphological patterns, enabling more objective and standardized embryo assessment. Consequently, AI-supported methods may improve the accuracy of identifying embryos with high implantation potential and may contribute to improved ART outcomes.[9]

AI algorithms trained on microscopic embryo images have been shown to accelerate and improve the accuracy of assessing developmental potential.[29,30] Khosravi et al.[31] developed a deep-learning platform trained with blastocyst images classified as good or poor quality by embryologists, achieving a fully automated workflow with 96% accuracy. These findings emphasize the potential of AI tools to reduce workload while enhancing consistency in embryo quality assessment.

Embryonic aneuploidy remains the leading cause of IVF failure, contributing to implantation failure and recurrent miscarriage.[32] Ploidy assessment via preimplantation genetic testing for aneuploidy (PGT-A) is widely used to identify euploid embryos for transfer. However, because PGT-A requires a trophectoderm biopsy, its invasive nature may introduce risks such as impaired embryo integrity and reduced implantation potential.[28]

Recent advances demonstrate that AI technologies can non-invasively predict embryo ploidy status using imaging and clinical data. Kato et al.[33] reported that existing AI-based, morphokinetic, and morphological embryo selection models showed associations with blastocyst euploidy rates. Likewise, Jiang et al.[34] integrated patient characteristics such as age, AMH levels, and sperm quality with blastocyst images, yielding significantly improved predictive accuracy.[9] These approaches offer the promise of selecting embryos with higher implantation potential without the risks associated with biopsy.[35]

However, the use of AI-based non-invasive ploidy prediction introduces important ethical considerations. False-positive predictions may result in the unjustified exclusion of potentially viable euploid embryos, whereas false-negative predictions could lead to the transfer of aneuploid embryos and associated adverse outcomes. These risks highlight the need for rigorous validation, transparent algorithmic reporting, and careful clinical oversight to ensure that AI-assisted embryo selection remains both safe and ethically responsible.

Prediction of Implantation Success

As a critical determinant of treatment success in ART, predicting which embryo is most likely to implant enables clinicians to optimize embryo selection and improve overall pregnancy outcomes. In the study by Fitz et al.,[36] which compared embryologists' performance in selecting day 5 euploid blastocysts with and without AI assistance, embryologists correctly selected the embryo that resulted in successful implantation 65.5% of the time without AI, whereas the accuracy increased to 73.6% with AI support. Across all participating embryologists, the average improvement in selecting the embryo with the highest implantation potential was 11.1% with AI assistance. Although no statistically significant differences were observed based on the level of experience, a more pronounced improvement trend was noted among less experienced embryologists.

Prediction of Clinical Outcomes and Designing Individualized Treatment Protocols

AI is increasingly being utilized to predict clinical pregnancy outcomes in ART.[6] By integrating diverse clinical variables, including demographic factors, medical and reproductive history, cause of infertility, comorbidities, and previous ART attempts, AI models can estimate individualized success probabilities prior to treatment.[10] Goyal et al.[37] conducted a large-scale study evaluating AI models trained on 25 clinical parameters from 141,160 patients to predict the likelihood of live birth in IVF. The study demonstrated that excluding variables reduced model accuracy, emphasizing that the combined effect of multiple clinical features enhances predictive performance. These findings highlight the potential of AI as a clinical decision-support tool in estimating personalized treatment outcomes in IVF.

Building on these predictive capabilities, AI can also contribute to the design of individualized ovarian stimulation and treatment protocols. By analyzing patient-specific patterns within large datasets, AI systems can recommend tailored treatment strategies that may improve clinical efficiency and reduce the trial-and-error approach often observed in ART cycles. This personalized method aims to enhance treatment success while minimizing the burden associated with repeated unsuccessful attempts.

The Use of Micromanipulation and Robotic Applications in the ART Laboratory

The use of robotic systems in embryo culture, monitoring, and cryopreservation contributes to automation and optimization in ART laboratories by reducing errors and improving record-keeping practices.[4] In a recently published groundbreaking case report, Mendizabal-Ruiz et al.[38] described a robot-assisted, digitally controlled, and remotely operated intracytoplasmic ICSI system and reported the first successful live birth achieved using this platform. The robotic system autonomously performed approximately half of the 23 micromanipulation steps involved in ICSI, while the remaining procedures were executed remotely by an operator via digital commands. The platform integrates advanced technologies such as AI-assisted sperm selection, laser-based sperm immobilization, zona pellucida thinning using laser, and piezo-assisted injection. In clinical application, one of the blastocysts derived from oocytes fertilized via remote robotic ICSI resulted in a successful pregnancy and the birth of a healthy baby. This study represents the first clinical success demonstrating the feasibility of robotic automation in ART and marks a significant milestone in enhancing standardization and global accessibility of laboratory procedures.

Ethical Concerns Regarding the Use of Artificial Intelligence in Assisted Reproductive Technologies

The integration of AI into ART necessitates not only clinical considerations but also a range of ethical evaluations. As these technologies operate directly on patient data, issues such as the protection of privacy, transparency in the informed consent process, and equitable access to services must be carefully addressed.[8]

In reproductive medicine, AI systems analyze individuals' genetic information, fertility-related medical history, and biological data. Therefore, ensuring the security of personal health information is not only a legal obligation but also an ethical imperative.[8] Data protection frameworks such as the European Union's General Data Protection Regulation (GDPR) and Türkiye's Personal Data Protection Law (KVKK) impose strict requirements for the processing of sensitive health data in clinical and laboratory workflows. Within this context, the anonymization or pseudonymization of datasets, restriction of third-party access, and the provision of transparent information regarding how AI systems use patient data during the informed consent process are of primary importance.

The inclusion of AI as a decision-support tool in clinical workflows does not absolve physicians of responsibility. Technological recommendations must always be interpreted alongside expert clinical judgment.[8] In cases in which AI-generated suggestions conflict with clinical assessment, final decisions must be made by healthcare professionals in accordance with medical ethical principles. Furthermore, in the event of adverse outcomes resulting from AI-generated predictions, responsibility must be clearly defined—whether it lies with software developers, healthcare institutions, or physicians.

Laboratory-based risks also warrant attention, as insufficiently validated AI tools may increase the likelihood of misclassification, embryo misidentification, or inappropriate embryo selection, underscoring the need for rigorous quality control and oversight.[9] To ensure the ethical implementation of AI, a multidisciplinary approach is required. Effective collaboration among technology developers, healthcare professionals, legal experts, and ethics committees is necessary to guarantee that these systems are developed in compliance with both technical and ethical standards.[8,9]

To address these challenges, several regulatory and governance pathways can guide the safe integration of AI into ART. Agencies such as the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA) have introduced frameworks emphasizing transparency, clinical validation, and post-market surveillance for AI-based medical technologies. Similarly, the Turkish Ministry of Health provides regulatory guidance through national medical device and digital health regulations. Implementing standardized reporting systems, external validation mechanisms, algorithmic audit procedures, and structured informed-consent models can help mitigate data-security risks, reduce algorithmic bias, and support the ethical and responsible adoption of AI-driven tools in reproductive medicine.

The Future of Artificial Intelligence in Assisted Reproductive Technologies and Potential Innovations

In the future, AI is expected to become a fundamental tool for clinical decision support throughout the entire ART process—from ovarian stimulation to embryo transfer. This transformation will not only accelerate procedures but also promote the widespread adoption of personalized treatment plans that take into account individuals' genetic profiles, hormonal status, and environmental factors.[8] In procedures requiring micromanipulation, the reduction of human error is likely to positively influence success rates; moreover, the concept of AI-driven, fully automated embryology laboratories is becoming increasingly tangible.[4,8]

However, these technological advancements also raise important concerns. In particular, data security, algorithmic bias, ethical practice, and regulatory gaps stand out as critical issues that shape the integration of AI into clinical practice.[5] If these challenges can be successfully addressed, AI-supported ART applications will not only enhance success rates but also transform reproductive medicine into a more personalized, predictable, and safer domain—ultimately paving the way for healthier pregnancies.[4,8]

Conclusion

The use of AI in ART is rapidly expanding across both laboratory and clinical domains. Numerous AI-based algorithms have been developed not only for quality control in ART laboratories but also for enabling standardized and objective evaluations in steps traditionally dependent on embryologist expertise, such as oocyte quality assessment, sperm selection, ploidy prediction, embryo selection, and micromanipulation. By reducing subjectivity and improving reproducibility, these technologies contribute to more consistent decision-making and enhanced treatment efficiency. Moreover, AI-driven models show promise in predicting implantation success and generating personalized treatment protocols, offering opportunities to further refine clinical outcomes.

In conclusion, the integration of AI into infertility treatment through ART holds substantial potential to transform reproductive medicine. However, to translate this potential into routine clinical practice, more multifunctional and comprehensive models, expanded research efforts, large-scale randomized clinical trials, and interdisciplinary collaboration are needed.[4,6,9,29] It is equally important to recognize that current evidence is predominantly based on retrospective, single-center studies with limited sample sizes and a lack of randomized controlled trials, which restricts the generalizability of existing findings. Strengthening the evidence base through robust, well-designed studies will therefore be essential for the safe, reliable, and ethically responsible implementation of AI-assisted approaches in ART.

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