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AI-Enhanced PGT-A Protocols for Optimized Embryo Selection in Clinical Settings: Preimplantation Genetic Testing (PGT), Genetic Screening, and Next-Generation Sequencing (NGS) in Gender-Specific Genetic Disease Mitigation

Yash Srivastav[1*], Shivani Singh[1], Stuti Verma[2], Amita Singh[1], Saroj Kumar[1], Kamini Prajapati[1], Anup Kumar Sirbaiya[3]
[1]D.K.R.R Pharmacy College, Amberpur, Sitapur (Uttar Pradesh), India. 261303
[2]Aryakul College of Pharmacy and Research, Sitapur, Uttar Pradesh, India. 261303
[3]K.P. Singh Memorial Institute of Pharmacy, Sitapur, U.P, India.

***Corresponding Author E-mail: yashsrv.108@gmail.com**

Abstract:

AI-powered preimplantation genetic testing for aneuploidy (PGT-A) with next-generation sequencing (NGS) and time-lapse embryo monitoring is a notable breakthrough in assisted reproductive technologies (ARTs), mainly in vitro fertilization (IVF). This review discusses the significance of integrating NGS, AI, and time-lapse monitoring technologies to enable objective assessment of embryos through accurate evaluation of their morphology, morphokinetics, and genetic abnormalities. NGS improves embryo analysis by identifying genetic defects like aneuploidy, mosaicism, and monogenic diseases. On the other hand, AI increases the predictability of implantation outcomes by reducing the impact of bias in embryo selection. Integration of the technologies increases chances of success by improving implantation rates, minimizing risks of pregnancy loss due to chromosomal abnormalities, and increasing rates of live births. Advanced age and recurrent implantation failures are notable factors that increase the need for such a combination of technologies to improve IVF success rate. Moreover, AI-enabled PGT-A plays an important role in preventing hereditary and sex-based genetic diseases, for example, hemophilia and Duchenne muscular dystrophy. All in all, this review shows that AI-driven genomic and embryology integration has immense potential in transforming reproductive medicine, despite further validation and regulation still being needed.

Keywords: Artificial Intelligence, Preimplantation Genetic Testing for Aneuploidy (PGT-A), Next-Generation Sequencing (NGS), Embryo Selection, IVF, Time-Lapse Imaging, Genetic Screening, Reproductive Medicine.

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1. INTRODUCTION

The use of Artificial Intelligence (AI)-supported Preimplantation Genetic Testing for Aneuploidy (PGT-A) represents a great leap forward in Assisted Reproductive Technologies (ART). Conventional means of assessing embryos were based on embryologists' subjective judgment regarding their morphology [1]. However, the incorporation of AI into preimplantation genetic testing has brought tremendous changes to embryo selection during In Vitro Fertilization (IVF) procedures. AI-supported techniques are characterized by higher accuracy and precision as compared to traditional embryo assessments. This includes the use of machine learning algorithms, time-lapse imagery of embryo development, and Next-Generation Sequencing (NGS). Such techniques allow for the consistent identification of chromosome abnormalities and the prediction of embryo viability during IVF procedures.

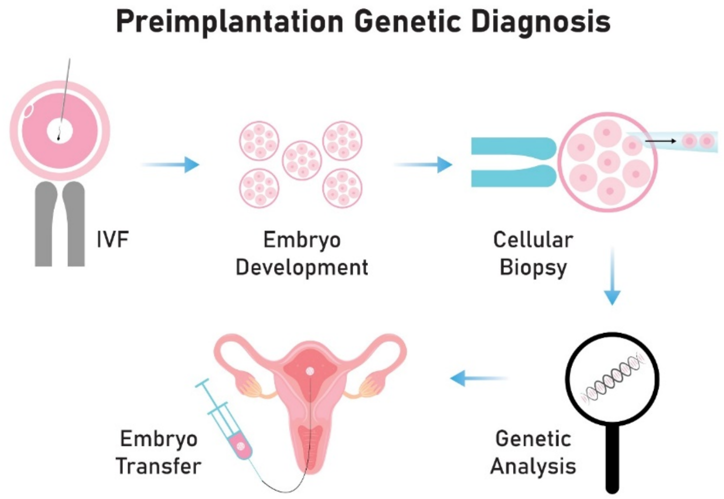

Figure 1: Preimplantation Genetic Testing [2]

Aside from increasing the success rate in IVF treatments, the use of AI-enhanced PGT-A techniques is instrumental in minimizing the risk of transmitting genetic disorders that affect a particular gender, namely males, such as hemophilia, Duchenne muscular dystrophy, and fragile X syndrome. The use of embryo screening using AI technology combined with the development of genomics allows for personalized fertility treatments through genetic, developmental, and clinical integration. Despite the positive impact of these technologies in the clinical setting, issues that revolve around ethics, data privacy, algorithmic transparency, prohibitive cost of procedures, and lack of regulation remain salient concerns [3].

1.1 Background Information and Context

The development of ARTs and Reproductive Genetics is responsible for major changes in infertility therapy and hereditary disease prevention. PGT-A coupled with NGS is an innovative method utilized to screen for chromosomally normal embryos within IVF cycles. Embryo selection techniques were traditionally based on visual assessments, which included the subjective opinion of professionals and varying clinical results [4]. The use of Artificial Intelligence (AI), machine learning, and Time-Lapse Embryo Imaging Systems represents a breakthrough in objective and more accurate methods for assessing embryos. AI-driven ARTs provide better insights into embryo developmental kinetics, genomic constitution, and implantation capacity, which improves embryo selection and minimizes the possibility of implantation failure and spontaneous abortions. The implementation of these technologies is especially valuable for the prevention of sex-linked genetic disorders, including hemophilia, Duchenne muscular dystrophy, fragile X syndrome, and other X-linked conditions.

1.2 Objectives of the Review

The primary objective of this review is:

- To examine the use of AI-assisted Preimplantation Genetic Testing for Aneuploidy (PGT-A) in enhancing embryo selection and clinical results of assisted conception.
- To review the implementation of Next-Generation Sequencing (NGS) techniques in PGT-A and their efficiency in identification of chromosomal abnormalities and congenital anomalies.
- To assess the impact of artificial intelligence and time-lapse imaging of embryos in assessing viability of embryos and optimizing chances of successful reproductive outcome.
- To explore the application of AI-assisted reproductive technologies in preventing gender- and X-linked conditions through early-stage screening.
- To review and discuss the technical, regulatory, and other concerns involved in using AI-supported PGT-A and NGS procedures.

1.3 Importance of the Topic

The rise of infertility, postponed childbearing, recurring pregnancy losses, and genetic illnesses passed down through generations have created a need for more precise reproductive techniques. There are several advantages that AI-assisted PGT-A and NGS provide in terms of clinical utility. They include higher embryo implantation success rates, better pregnancy outcomes, decreased risks of passing genetic disorders to offspring, and precision fertility medicine [5]. Moreover, they eliminate subjective bias in embryo grading and allow tailored treatment based on the unique genetics and development of embryos. However, while offering great clinical value, there are still issues connected to ethical concerns, high expenses, data confidentiality, lack of explainability of algorithms, and lack of standardization that should not be overlooked. Hence, it is crucial to recognize the clinical relevance of AI-based fertility medicine, its shortcomings, and future prospects.

2. AI-INTEGRATED PGT-A AND NGS APPROACHES FOR ADVANCED EMBRYO SELECTION

The use of AI-based PGT-A and NGS enhances embryo selection, genetic screening, and IVF through better identification of healthy embryos and minimizing the incidence of genetic disorders but is not without limitations including cost implications and ethical considerations [6].

2.1 Overview of Preimplantation Genetic Testing (PGT)

Preimplantation Genetic Testing (PGT) is an innovative technique in reproductive genetics that involves screening embryos conceived via In Vitro Fertilization (IVF) [7]. The aim of preimplantation genetic testing is to detect the presence of healthy and genetically normal embryos so as to increase implantation rate, decrease the chance of miscarriages, and avoid passing on heritable genetic conditions to offspring. Preimplantation genetic testing has played a significant role in reproductive medicine over the last decade among infertile patients, those with recurrent abortions, women of advanced maternal age, and families with a genetic disorder.

The types of PGT can be generally categorized into three main categories:

- **PGT-A (Preimplantation Genetic Testing for Aneuploidy):** Used to identify chromosomal abnormalities such as trisomy or monosomy.
- **PGT-M (Preimplantation Genetic Testing for Monogenic Disorders):** Used for detecting single-gene inherited disorders such as cystic fibrosis, thalassemia, and hemophilia.
- **PGT-SR (Preimplantation Genetic Testing for Structural Rearrangements):** Used to detect chromosomal translocations, inversions, and other structural abnormalities [8].

Of all the mentioned above techniques, PGT-A is the most widely used one as numerical chromosome aberrations play a critical role in causing implantation problems, pregnancy loss, and birth defects. Numerical chromosome abnormalities often arise during embryogenesis, especially among those who conceive at an older age [9].

2.2 Artificial Intelligence in Embryo Selection

✚ AI-Based Embryo Imaging Systems

AI technology has revolutionized the field of reproductive medicine through automated embryo evaluation platforms. In the past, embryo evaluation depended on visual analysis under the microscope by the embryologist [10]. This process involved subjective assessments that led to inaccurate and consistent results. AI-assisted embryo imaging techniques enable accurate and consistent embryo evaluation.

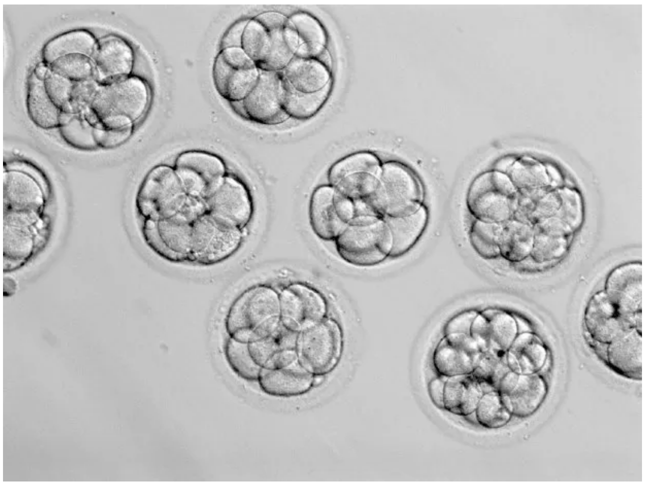

Figure 2: Embryo Imaging Systems [11]

AI-based embryo evaluation platforms incorporate time-lapse imaging technologies integrated with machine learning and deep learning algorithms for constant monitoring of embryo development. The AI-based algorithms evaluate various parameters including embryo morphology, timing of cell division, blastocyst formation, extent of embryo fragmentation, cellular symmetry, and kinetics of embryo development [12].

Machine learning models learn from extensive databases comprising embryo image data sets and corresponding clinical outcomes. Such data include the probability of implantation, pregnancy rates, and successful delivery of the baby. Through pattern recognition and predictive analysis, the algorithms predict embryo viability and implantation potential [13].

Key Human-Based Clinical Findings

Human clinical studies conducted recently have shown that AI embryo scoring systems attain prediction results similar to or even better than those obtained by trained embryologists. AI-powered embryo scoring has led to advancements in:

- Embryo implantation rates
- Clinical pregnancy outcomes
- Live birth prediction accuracy
- Embryo viability assessment
- Reduction in observer-dependent variability
- Consistency in embryo grading across fertility centers

Also, with artificial intelligence systems, embryos can be monitored continuously without ever removing them from incubators; this will ensure that embryos stay in a conducive environment for development [14]. There are many examples of AI-based embryo ranking systems which help in carrying out single embryo transfer procedures in IVF centers.

2.3 Next-Generation Sequencing (NGS) in PGT-A

Principles of NGS-Based Genetic Screening

Advances in Next-Generation Sequencing (NGS) have transformed genetic screening in reproductive medicine through the application of extensive, rapid genomic analysis with unmatched accuracy and sensitivity [15]. The technology facilitates the simultaneous sequencing of millions of pieces of DNA, providing precise chromosomal information from biopsy materials taken from the embryo.

During PGT-A testing, NGS is applied mainly for the detection of chromosomal aneuploidy, segmental deletions, duplications, and mosaicism in the embryos. When compared to previous technologies such as FISH and aCGH, NGS presents several advantages due to the superior genomic resolution and accuracy it provides [16].

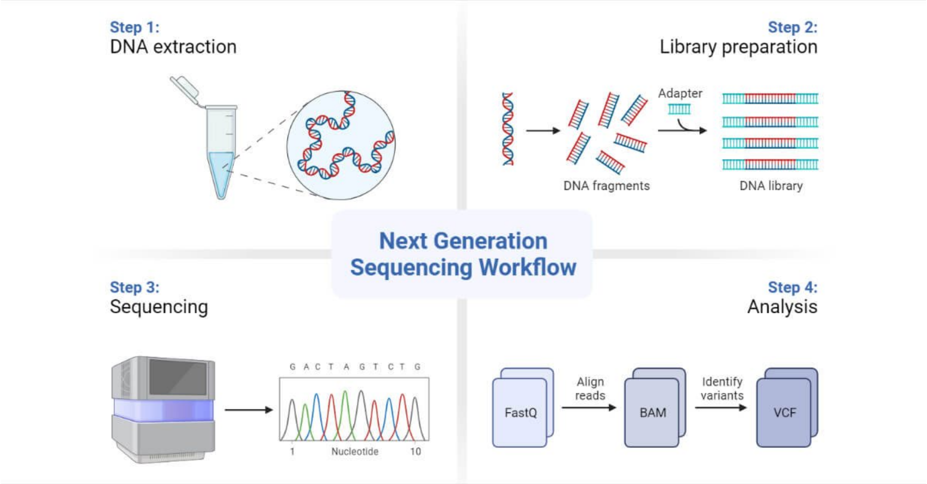

Figure 3: Next-Generation Sequencing (NGS) [17]

Several benefits are presented when using NGS for genetic screening:

- Higher sensitivity for detecting chromosomal abnormalities
- Improved specificity and diagnostic reliability
- Better detection of low-level embryo mosaicism
- Comprehensive whole-chromosome analysis
- Simultaneous evaluation of multiple genetic abnormalities

This technology has made great improvements in the process of identifying euploid and non-euploid embryos hence increasing embryo selection efficiency during the process of IVF [18].

Human Clinical Applications

Human IVF research has shown that the use of PGT-A through NGS significantly enhances reproductive success through the identification of genetically normal embryos for implantation. The clinical studies revealed a number of benefits, including:

- Higher implantation success rates
- Reduced miscarriage frequency
- Increased live birth rates
- Improved outcomes in women of advanced maternal age
- Better embryo selection in recurrent implantation failure cases
- Improved reproductive planning for couples with inherited disorders

Furthermore, it has made possible a hybrid approach whereby chromosomes and monogenes can be tested together [19]. This method is especially useful in identifying inherited conditions in high-risk patients who could be carriers of hemophilia, fragile X syndrome, or Duchenne muscular dystrophy.

Moreover, PGT-A using NGS enables personalized fertility treatments since the selection of embryos with the most developmental and genetic promise is possible.

2.4 Strengths and Weaknesses

Strengths

- **Early Detection of Genetic Abnormalities:** PGT and NGS screening allows for detecting chromosomal anomalies as well as heritable genetic diseases before transferring the embryo. This helps to minimize chances of miscarriage, infertility issues, and passing on genetically inherited diseases.
- **Improved Embryo Selection Accuracy:** AI-enabled embryo assessment systems help grade embryos objectively through analysis of embryo morphology, kinetics, and implantation capacity. This reduces subjectivity that accompanies embryo assessment manually performed by an embryologist.
- **Enhanced IVF Success Rates:** Clinical trials conducted on human in vitro fertilization cycles have confirmed that artificial intelligence (AI)-assisted PGT-A and next-generation sequencing (NGS) screening increase implantation success, clinical pregnancy, and live birth rates, especially among older women and those with recurrent implantation failures.
- **Reduction in Inherited Genetic Diseases:** The PGT-M and NGS techniques can be used to prevent inherited diseases such as hemophilia, Duchenne muscular dystrophy, and fragile X syndrome through the identification of healthy embryos prior to implantation.
- **Continuous and Non-Invasive Embryo Monitoring:** AI-based time-lapse imaging technology observes embryo development processes constantly while not interrupting embryo culture environments; thus, it keeps constant laboratory environments for embryos.

Weaknesses

- **High Procedural and Infrastructure Costs:** High-end laboratory tools, sequencing platforms, imaging techniques, and personnel expertise are essential for AI-assisted PGT-A and NGS, which renders these tools inaccessible to underprivileged healthcare facilities.
- **Risk of Embryo Mosaicism:** Embryo mosaicism continues to be a difficult problem for patients due to the presence of normal and abnormal cells in embryos that causes uncertainty in diagnosis and embryo transfers.
- **Dependence on High-Quality Data:** Machine learning algorithms depend on extensive and quality training datasets. Low-quality datasets may result in reduced predictive accuracy and generalizability across various population groups and IVF centers.
- **Ethical and Regulatory Concerns:** Ethical issues arise from embryo genetic screening due to embryo selection, reproductive autonomy, misuse of technology in non-medical sex selection, and genetic discrimination. There are also wide differences in regulatory standards across countries [20].
- **Limited Algorithm Transparency:** A significant number of AI-based systems operate like "black box" models, making it challenging for clinicians to comprehend the entire process of making decisions about selecting embryos. The lack of transparency can lower levels of clinical trust and regulatory acceptance.

3. ADVANCED AI AND NGS APPLICATIONS IN EMBRYO SELECTION AND GENETIC DISEASE PREVENTION

AI-assisted reproductive technology enables better embryo imaging, genetic testing, and personalized treatment of IVF through time-lapse imaging, PGT-A, PGT-M, and next-generation sequencing methods. They assist in choosing healthy embryos, minimizing genetic disorder inheritance risks, increasing implantation efficiency, and providing precise fertility treatment despite ongoing issues of ethics, cost, and regulation [21].

3.1 AI and Time-Lapse Embryo Monitoring

One such technological breakthrough is the time-lapse monitoring system of embryos that facilitates non-invasive monitoring of embryo development. Traditional techniques involved removal of embryos from their culture environment to assess their developmental progress under a microscope. However, this practice exposed embryos to factors such as changes in temperature, light, and pH, which could adversely affect their development. Time-lapse embryo imaging systems offer solutions to these challenges by providing high-resolution images of embryos in controlled incubation environments.

AI technology incorporated into time-lapse embryo imaging systems analyzes large datasets to identify morphokinetic profiles of viable embryos. Such AI-based platforms consider multiple parameters of embryo development, including:

- Cell division timing
- Blastocyst formation dynamics
- Fragmentation patterns
- Symmetry of blastomeres
- Rate of embryo cleavage
- Inner cell mass quality
- Trophectoderm morphology

Machine learning and deep learning algorithms evaluate these attributes in relation to past medical records of clinical databases to determine the potential for embryo implantation and reproduction [22]. AI-assisted programs can analyze numerous images of embryos quickly and detect slight changes in development patterns that might not be readily identifiable through manual assessment by embryologists.

Clinical trials on humans have shown that the use of AI along with embryo time-lapse monitoring enhances embryo ranking and selection capabilities. Some in vitro fertilization facilities have observed improved embryo implantation and clinical pregnancy rates with the integration of AI-assisted embryo ranking tools within the IVF procedure workflow. It also enables single embryo transfer methods by ensuring high-confidence embryo selection.

Clinical Significance

The integration of AI and time-lapse imaging provides several important clinical benefits:

- Decreased rate of multiple pregnancies due to better selection of embryos for transfer

- Greater ability to predict the viability of embryos for implantation
- More accurate monitoring of embryo culture without disrupting the environment
- Minimized subjectivity by embryologists
- Accurate evaluation of embryo quality
- Greater efficiency in laboratory procedures

Challenges and Limitations

Despite promising clinical outcomes, certain challenges remain associated with AI-assisted time-lapse systems:

- Equipment and operation cost
- Large size and quality of clinical data sets required
- Non-uniform imaging protocol at fertility clinics
- Lack of standardized AI algorithms
- Multicenter study needed for clinical validation
- Ethical issues with embryo selection using AI

Further technological developments and standardization of procedures are anticipated to enhance the effectiveness and availability of AI-based embryo monitoring technology in future reproductive medicine practice [23].

3.2 Gender-Specific Genetic Disease Mitigation

X-Linked Genetic Disorders

Mitigation of genetically caused diseases in gender-specific cases has emerged as one of the most important uses of PGT-M in conjunction with PGT-A and modern genomic screening techniques [24]. This is because numerous genetic diseases are caused by mutations in genes present in the X chromosome and men, who only have one X chromosome, receive it from their mother.

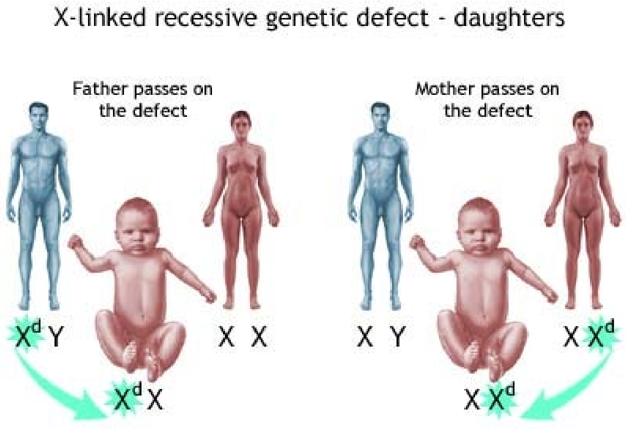

Figure 4: X-Linked Genetic Disorders [25]

These diseases can result in debilitating physical, mental, or hemodynamic problems that drastically impact the quality of life of individuals. The use of IVF along with PGT allows the screening of embryos for any genetic disorders before implantation to prevent disease inheritance.

Some common types of X-linked diseases screened using IVF are:

- Hemophilia A and Hemophilia B
- Duchenne muscular dystrophy
- Becker muscular dystrophy
- Fragile X syndrome
- Hunter syndrome
- X-linked spinal muscular atrophy

PGT-M enables the detection of certain genetic mutations in the embryo, whereas PGT-A assesses the chromosomal integrity of the embryo. This strategy enhances the chances of selecting genetically normal embryos with increased implantation capabilities.

Role of AI and NGS

AI technology and NGS have revolutionized the efficiency and precision with which genetic disorders can be identified in reproduction genetics. NGS provides complete genetic profiling with increased sensitivity, making it possible to detect monogenic conditions, chromosomal disorders, and even mosaicism at once [26].

AI helps improve the efficiency of the analysis process by quickly processing complex genetic profiles and detecting patterns with genetic relevance. The machine learning algorithms help differentiate between healthy embryos and affected embryos with greater precision.

AI helps prioritize embryos automatically through:

- Embryo morphology
- Morphokinetic developmental data
- Chromosomal screening results
- Genetic mutation profiles
- Clinical reproductive history

Embryos that are genetically healthy or carrier-negative can be chosen for embryo transfer, thus reducing the chances of passing on serious genetic disorders to future generations.

3.3 Personalized Reproductive Medicine

Personalized reproductive medicine is an emerging method in the field of infertility that involves making clinical decisions based on unique attributes of patients, their reproductive health record, and their genetic makeup. The application of artificial intelligence, genomics, and predictive models has played an important role in facilitating more personalized treatment approaches through IVF techniques.

Artificial intelligence-powered reproductive medicine uses many aspects related to patients for producing personalized predictions in terms of embryo survival chances, implantation success, and reproductive health:

- Patient age
- Hormonal profiles
- Ovarian reserve markers
- Embryo morphokinetics
- Genetic screening results
- Previous IVF outcomes
- Endometrial receptivity data
- Lifestyle and clinical history

Machine Learning algorithms employ huge clinical databases to recognize patterns related to successful pregnancy and birth. Through incorporation of both the genetics and development of embryos, AI algorithms help clinicians to select those embryos that have maximum chances of success while reducing cases of unsuccessful implantations and repetitive IVF cycles [27].

AI-based prediction models can also improve protocols of ovarian stimulation, timing of embryo transfers, and treatment plans for patients suffering from implantation failures.

Challenges and Future Directions

Despite significant progress, personalized reproductive medicine faces several ongoing challenges:

- Necessity of large-scale multi-center testing
- Privacy and security issues
- Insufficient algorithmic transparency
- Inconsistency in the performance of AI systems between groups
- High implementation costs
- Ethical issues related to predictive reproductive technologies

Future studies should concentrate on the enhancement of explainable AI technologies, creating standardized international clinical guidelines, and ensuring access to modern fertility techniques across different healthcare facilities.

4. ETHICAL, LEGAL, AND REGULATORY CONSIDERATIONS IN AI-ENHANCED PGT-A

The quick introduction of artificial intelligence (AI), Next Generation Sequencing (NGS), and other genetic screening techniques into the field of Preimplantation Genetic Testing for

Aneuploidy (PGT-A) presents numerous ethical, legal, and regulatory issues in reproductive medicine. While these innovations bring about immense advantages in enhancing the precision of embryo selection and minimizing the chances of inheritance of genetic diseases, there are also certain worries concerning reproductive rights, embryo selection issues, patient data protection, and health care equity [28].

Among the most serious ethical problems is non-medical embryo selection, especially that related to sex selection for socially based reasons rather than medical reasons. Gender-specific tests are indeed medically necessary for avoiding the development of X-linked hereditary conditions like hemophilia and Duchenne muscular dystrophy; however, their application for non-medical needs can lead to imbalances [29].

The second critical problem involves the management of sensitive genetic data collected through AI-assisted genomic analyses. Due to their need for large data pools for learning purposes, AI tools present potential threats to the privacy of patients, their right to give an informed consent, as well as their property and security issues. The careful management of reproductive genetic data is a crucial element that would enable patients' protection from unauthorized use of such data [30].

Table 1: Summary of Literature on Next-Generation Sequencing, Liquid Biopsy, and Preimplantation Genetic Testing [31]

Author(s) & Year	Study Focus	Methodology/Approach	Key Findings
Tonge & Gant (2016) [32]	Analysis of the human circulating microRNAome using next-generation sequencing	Next-generation sequencing-based molecular analysis of circulating microRNAs	Reported that next-generation sequencing enabled highly sensitive and comprehensive detection of circulating microRNAs. The study highlighted the potential of circulating microRNAs as non-invasive biomarkers for disease diagnosis, prognosis, and personalized medicine applications.
Unsal et al. (2025) [33]	Efficacy of targeted enrichment protocols in PGT-M applications	Comprehensive analysis of targeted sequencing and enrichment methodologies in preimplantation genetic testing	Demonstrated that targeted enrichment protocols improved mutation detection sensitivity, reduced diagnostic errors, and enhanced the reliability of embryo genetic screening. The study

			emphasized the importance of optimized sequencing strategies for accurate embryo selection and improved reproductive outcomes.
Vanderhoff et al. (2024) [34]	Effects of multiple embryo manipulations in PGT-A cycles	Clinical analysis of repeated embryo biopsy and handling procedures in assisted reproductive treatments	Reported that multiple embryo manipulations were associated with reduced implantation rates and potentially inferior clinical outcomes. The study highlighted the need to minimize procedural stress and optimize embryo handling techniques to preserve embryo viability.
Veronez et al. (2016) [35]	Genetic analysis of hereditary angioedema using targeted next-generation sequencing	Family-based genetic investigation using targeted sequencing techniques	Found that targeted next-generation sequencing successfully identified clinically significant genetic variants associated with hereditary angioedema. The study demonstrated the effectiveness of sequencing technologies in improving molecular diagnosis and genetic counseling.
Vireque et al. (2025) [36]	Comparison of double versus single blastocyst biopsy and vitrification in PGT cycles	Protocol for systematic review and meta-analysis of clinical and neonatal outcomes	Emphasized that biopsy frequency and vitrification strategies significantly influenced embryo survival, implantation success, pregnancy outcomes, and neonatal health. The study highlighted the importance of evidence-based optimization of biopsy protocols in

			assisted reproductive technologies.

It is important to note that the policies that regulate AI-assisted reproductive techniques can greatly differ between countries. While some countries allow comprehensive embryo screening and selection, others strictly limit the scope of interventions performed within the framework of such techniques. Thus, there are no internationally recognized guidelines for AI-assisted PGT-A.

5. DISCUSSION

PGT-A with the help of AI together with NGS and time-lapse imaging helps increase embryo selection, implantation success rates, and live birth success [37]. The gaps in this area include no standardization, lack of validation, and lack of transparency in AI used. Further areas of study need to be in explainable AI and the inclusion of omics technologies, amongst other things.

5.1 Interpretation and Analysis of Findings

Based on the results obtained from this literature review, the use of AI-assisted PGT-A combined with NGS and time-lapse embryo assessment contributes greatly to improving the efficacy of embryo selection in IVF procedures. AI tools can minimize subjectivity in embryo grading based on morphological and morphokinetic aspects, while NGS can provide higher precision in detecting chromosomal anomalies, mosaicism, and monogenic diseases [38]. As a result, the efficiency of implantation, pregnancy, and delivery increases, particularly in older patients experiencing RIF.

5.2 Implications and Significance

The incorporation of AI and genomics in reproductive medicine holds significant clinical implications. It facilitates individualized embryo selection through the combination of genetic, morphological, and clinical information, which helps improve decision-making during in vitro fertilization treatments. Moreover, such techniques help prevent inherited and sex-based genetic conditions like hemophilia and Duchenne muscular dystrophy. Nevertheless, factors like cost considerations, ethical considerations, and lack of availability hinder their widespread use in clinical practice.

5.3 Research Gaps and Future Research Directions

Though there have been many developments in AI-PGT-A, NGS, and time-lapse embryo analysis, various key knowledge gaps still exist [39]. Some of these include inadequate validation studies across centers for AI tools, inadequate standardization of the embryo assessment and NGS processes, and explainability challenges in AI-driven decision-making systems. In addition, inconsistent ethics and regulatory laws across various nations and privacy and algorithm bias issues are barriers to consistent application. Future investigations should aim to develop explainable AI models, incorporate multi-omics approaches for accurate prediction, and conduct large-scale multicenter clinical trials. Other priorities should be setting up global guidelines, enhancing cost-effective technology approaches, and carrying out studies for offspring health effects in the long run [40].

6. CONCLUSION

In conclusion, the use of AI-supported PGT-A together with NGS and time-lapse embryo screening is a significant step forward in assisted reproductive technology that allows a considerable improvement in embryo selection, implantation rates, and success results from IVF treatment. The use of advanced technologies and AI algorithms for embryo screening helps detect embryos with healthy chromosomal structure and no mutations, which reduces miscarriage risk and improves pregnancy chances. Additionally, the discussed methods help to prevent hereditary and gender-specific disorders such as the presence of genes that cause X-linked diseases. Besides that, the application of AI techniques helps develop personalized and precision reproductive medicine. At the same time, several issues related to costs, ethics, accessibility, and lack of standardization, as well as the lack of clarity regarding the used algorithms, prevent wider clinical applications of AI techniques. Thus, more work is needed in this field to make such innovative techniques applicable in clinics safely and effectively.

REFERENCES

1. Al Hashimi, B., Harvey, K. E., Harvey, S. C., Linara-Demakakou, E., Griffin, D. K., Ahuja, K., & Macklon, N. (2025). PGT-A can increase the number of embryos available for transfer by 'rescuing'morphologically poor-quality blastocysts: An analysis of nine years of data from a single centre. Reproductive BioMedicine Online, 105208.
2. Amin, N., Kteily, K., Deniz, S., Faghih, M., Karnis, M. F., Amin, S., & Neal, M. S. (2025). The ART of Embryo Selection: A Review of Methods to Rank the Most Competent Embryo (s) for Transfer to Optimize IVF Success. Biomedicines, 13(11), 2766.
3. Chang, Z., Chen, J., Chen, J., Zhu, Y., Zhang, Y., Liu, J., ... & Zeng, G. (2025). Precision diagnosis of preoperative infection in urolithiasis: integrating targeted next-generation sequencing for enhanced accuracy—a multicenter cohort study. BMC Infectious Diseases, 25(1), 1767.
4. Chang, Z., Deng, J., Zhang, J., Wu, H., Wu, Y., Bin, L., ... & Sun, B. (2025). Rapid and accurate diagnosis of urinary tract infections using targeted next-generation sequencing: A multicenter comparative study with metagenomic sequencing and traditional culture methods. Journal of Infection, 90(4), 106459.
5. Chow, J. F., Lam, K. K., Cheng, H. H., Lai, S. F., Yeung, W. S., & Ng, E. H. (2024). Optimizing non-invasive preimplantation genetic testing: investigating culture conditions, sample collection, and IVF treatment for improved non-invasive PGT-A results. Journal of Assisted Reproduction and Genetics, 41(2), 465-472.
6. Cunha, M. L., Meijers, J. C., & Middeldorp, S. (2015). Introduction to the analysis of next generation sequencing data and its application to venous thromboembolism. Thrombosis and Haemostasis, 114(11), 920-932.
7. Dargis, N., Lamontagne, M., Gaudreault, N., Sbarra, L., Henry, C., Pibarot, P., ... & Bossé, Y. (2016). Identification of gender-specific genetic variants in patients with bicuspid aortic valve. The American journal of cardiology, 117(3), 420-426.
8. Del Rey, J., Vidal, F., Ramírez, L., Borràs, N., Corrales, I., Garcia, I., ... & Navarro, J. (2018). Novel Double Factor PGT strategy analyzing blastocyst stage embryos in a single NGS procedure. PLoS One, 13(10), e0205692.
9. during Entry, N. (2017). Target Molecule Number Limits Next-Generation Sequencing Accuracy and Sensitivity.

10. García-Pascual, C. M., Navarro-Sánchez, L., Navarro, R., Martínez, L., Jiménez, J., Rodrigo, L., ... & Rubio, C. (2020). Optimized NGS approach for detection of aneuploidies and mosaicism in PGT-A and imbalances in PGT-SR. Genes, 11(7), 724.

11. Gordon, C. E., Keefe, K. W., Ginsburg, E. S., Racowsky, C., & Lanes, A. (2022). Embryo attrition in planned PGT-A: predicting the number of available blastocysts for transfer. Journal of Assisted Reproduction and Genetics, 39(1), 173-181.

12. Hwang, J., Bang, S., Choi, M. H., Hong, S. H., Kim, S. W., Lee, H. E., ... & Choi, Y. J. (2024). Discovery and validation of survival-specific genes in papillary renal cell carcinoma using a customized next-generation sequencing gene panel. Cancers, 16(11), 2006.

13. Kang, Y., Nam, S. H., Park, K. S., Kim, Y., Kim, J. W., Lee, E., ... & Park, I. (2018). DeviCNV: detection and visualization of exon-level copy number variants in targeted next-generation sequencing data. BMC bioinformatics, 19(1), 381.

14. King, A. C., & Zenker, A. K. (2023). Sex blind: bridging the gap between drug exposure and sex-related gene expression in Danio rerio using next-generation sequencing (NGS) data and a literature review to find the missing links in pharmaceutical and environmental toxicology studies. Frontiers in Toxicology, 5, 1187302.

15. Lizarraga, D., Huen, K., Combs, M., Escudero-Fung, M., Eskenazi, B., & Holland, N. (2016). miRNAs differentially expressed by next-generation sequencing in cord blood buffy coat samples of boys and girls. Epigenomics, 8(12), 1619-1635.

16. Ma, Y., Shi, N., Li, M., Chen, F., & Niu, H. (2015). Applications of next-generation sequencing in systemic autoimmune diseases. Genomics, Proteomics & Bioinformatics, 13(4), 242-249.

17. Mahmood, T. B., Saha, A., Hossan, M. I., Mizan, S., Arman, S. A. S., & Chowdhury, A. S. (2021). A next generation sequencing (NGS) analysis to reveal genomic and proteomic mutation landscapes of SARS-CoV-2 in South Asia. Current research in microbial sciences, 2, 100065.

18. Morales, C. (2024). Current applications and controversies in preimplantation genetic testing for aneuploidies (PGT-A) in in vitro fertilization. Reproductive Sciences, 31(1), 66-80.

19. Munné, S., Nakajima, S. T., Najmabadi, S., Sauer, M. V., Angle, M. J., Rivas, J. L., ... & Buster, J. E. (2020). First PGT-A using human in vivo blastocysts recovered by uterine lavage: comparison with matched IVF embryo controls. Human Reproduction, 35(1), 70-80.

20. Nuñez-Calonge, R., Santamaria, N., Rubio, T., & Moreno, J. M. (2024). Making and selecting the best embryo in in vitro fertilization. Archives of Medical Research, 55(8), 103068.

21. Pan, H. A., Tang, Y. A., Huang, I. N., Wang, C. Y., Chien, C. W., & Sun, H. S. (2025). Optimizing Non-Invasive PGT-A: A Multi-Factorial Approach for Enhanced Accuracy and Seamless Integration Into Clinical IVF. Reproductive Medicine and Biology, 24(1), e12688.

22. Pathania, A. (2025). Diverse Facets of Nonhuman Sequences in Read Outputs of the Human Next-Generation Sequencing Data and Their Relevance with Viruses. In Computational Virology (pp. 251-258). New York, NY: Springer US.

23. Popovic, M., Kalafat, E., Miguel-Escalada, I., Rodríguez-Aranda, A., & Sakkas, D. (2025). O-267 PGT-A provider strategies influence embryo selection and live birth rates: a multicenter analysis of 40,308 blastocyst biopsy results and 8,491 euploid embryo transfers. Human Reproduction, 40(Supplement_1), deaf097-267.

24. Ranjan, R., Yusuf, M. A., Uddin, M. N., Mamun, M. T., Mamun, A. A., Kawnayn, G., & Hakim, M. (2025). Gender-Specific Next-Generation Sequencing Reveals First Allelic Variation Patterns in Dementia Risk Among Bangladeshis: The CARED Study. International Journal of General Medicine, 6191-6199.

25. Reale, C., Invernizzi, F., Panteghini, C., & Garavaglia, B. (2023). Genetics, sex, and gender. Journal of Neuroscience Research, 101(5), 553-562.

26. Reeskamp, L. F., Balvers, M., Peter, J., van de Kerkhof, L., Klaaijsen, L. N., Motazacker, M. M., ... & Zuurbier, L. (2021). Intronic variant screening with targeted next-generation sequencing reveals first pseudoexon in LDLR in familial hypercholesterolemia. Atherosclerosis, 321, 14-20.

27. Sakkas, D., Navarro-Sánchez, L., Ardestani, G., Barroso, G., Bisioli, C., Boynukalin, K., ... & Rubio, C. (2024). The impact of implementing a non-invasive preimplantation genetic testing for aneuploidies (niPGT-A) embryo culture protocol on embryo viability and clinical outcomes. Human Reproduction, 39(9), 1952-1959.

28. Simopoulou, M., Sfakianoudis, K., Maziotis, E., Tsioulou, P., Grigoriadis, S., Rapani, A., ... & Pantos, K. (2021). PGT-A: who and when? A systematic review and network meta-analysis of RCTs. Journal of assisted reproduction and genetics, 38(8), 1939-1957.

29. Skillern, A., Leonard, W., Pike, J., & Mak, W. (2021). Growth hormone supplementation during ovarian stimulation improves oocyte and embryo outcomes in IVF/PGT-A cycles of women who are not poor responders. Journal of Assisted Reproduction and Genetics, 38(5), 1055-1060.

30. Sordia-Hernandez, L. H., Morales-Martinez, F. A., González-Colmenero, F. D., Flores-Rodriguez, A., Leyva-Camacho, P. C., Sordia-Piñeyro, M. O., ... & Sordia-Piñeyro, L. H. (2022). The effects of preimplantation genetic testing for aneuploidy (PGT-A) on patient-important outcomes in embryo transfer cases: a meta-analysis. Journal of Reproduction & Infertility, 23(4), 231.

31. Su, Y. J., Lin, I. C., Wang, L., Lu, C. H., Huang, Y. L., & Kuo, H. C. (2018). Next generation sequencing identifies miRNA-based biomarker panel for lupus nephritis. Oncotarget, 9(46), 27911.

32. Tonge, D. P., & Gant, T. W. (2016). What is normal? Next generation sequencing-driven analysis of the human circulating miRNAOme. BMC molecular biology, 17(1), 4.

33. Unsal, E., Ozer, L., Baltaci, V., Duman, T., Halicigil, C., Koc, Z., ... & Aktuna, S. (2025). Assessing the efficacy of targeted enrichment protocol in PGT-M applications: a comprehensive analysis. Journal of Assisted Reproduction and Genetics, 1-10.

34. Vanderhoff, A., Lanes, A., Go, K., Dobson, L., Ginsburg, E., Patel, J., & Srouji, S. S. (2024). Multiple embryo manipulations in PGT-A cycles may result in inferior clinical outcomes. Reproductive BioMedicine Online, 48(2), 103619.

35. Veronez, C. L., da Silva, E. D., Lima Teixeira, P. V., Cagini, N., Constantino-Silva, R. N., Grumach, A. S., ... & Pesquero, J. B. (2016). Genetic analysis of hereditary angioedema in a Brazilian family by targeted next generation sequencing. Biological chemistry, 397(4), 315-322.

36. Vireque, A. A., Stolakis, V., Berteli, T. S., Bertero, M. C., & Kofinas, J. (2025). Double versus single blastocyst biopsy and vitrification in preimplantation genetic testing (PGT) cycles: protocol for a systematic review and meta-analysis of clinical and neonatal outcomes. Systematic Reviews, 14(1), 93.
37. Yadav, S., Tripathi, V., & Saran, V. (2023). Identification of Age and Gender Specific Bacteria in Human Saliva through Next-Generation Sequencing. Indian Journal of Forensic Medicine and Toxicology, 17(4).
38. Yiallouros, P. K., Kouis, P., Kyriacou, K., Evriviadou, A., Anagnostopoulou, P., Matthaiou, A., ... & Hadjisavvas, A. (2021). Implementation of multigene panel NGS diagnosis in the national primary ciliary dyskinesia cohort of Cyprus: an island with a high disease prevalence. Human Mutation, 42(6), e62-e77.
39. Yska, H. A., Elsink, K., Kuijpers, T. W., Frederix, G. W., van Gijn, M. E., & van Montfrans, J. M. (2019). Diagnostic yield of next generation sequencing in genetically undiagnosed patients with primary immunodeficiencies: a systematic review. Journal of Clinical Immunology, 39(6), 577-591.
40. Zhu, J., Xu, S., Hua, W., Wang, M., Zhang, S., Lu, P., & Wu, H. (2025). Targeted next-generation sequencing reveals genomic differences between male and female breast cancer. Translational Cancer Research, 14(12), 8313-8328.