Annals of Clinical and Medical Case Reports®

Mini Review **ISSN 2639-8109 | Volume 14**

A New Perspective on Sperm Analysis Through Artificial Intelligence: The Path Toward Personalized Reproductive Medicine

Gongora A[1*] and Barajas T[2]

[1]Centro de Fertilidad Humana en Mexico, Mexico City

[2]VITAFERT, Guadalajara, Mexico

[*]Corresponding author:

Alfredo Gongora,
Centro de Fertilidad Humana en Mexico,
Mexico City

Received: 08 Jan 2025
Accepted: 12 Feb 2025
Published: 18 Feb 2025
J Short Name: ACMCR

Keywords:

Artificial Intelligence; Male Infertility; Sperm Analysis; Assisted Reproduction; Personalized Reproductive Medicine; Machine Learning; Deep Learning; Sperm Morphology; Semen Assessment; Epigenetics

Citation:

Gongora A. A New Perspective on Sperm Analysis Through Artificial Intelligence: The Path Toward Personalized Reproductive Medicine.
Ann Clin Med Case Rep® 2025; V14(11): 1-10

1. Abstract

Male infertility is a significant factor in approximately 40% of couples experiencing primary or secondary infertility, posing a major biomedical and social challenge. Traditional sperm evaluation, based on the World Health Organization (WHO) criteria, provides a basic assessment of semen concentration, motility, and morphology. However, these methodologies face considerable limitations, including inter- and intra-observer variability, limited functional and molecular insights, and the absence of integrative criteria that encompass clinical, genomic, and epigenetic data.In recent decades, artificial intelligence (AI) has emerged as a pivotal tool for analyzing large datasets, recognizing complex patterns, and developing predictive models. In reproductive medicine, AI is playing a transformative role by enhancing diagnostic and prognostic accuracy while paving the way for personalized reproductive healthcare. Machine learning and deep learning applications are automating processes that previously relied almost exclusively on human expertise, enabling an unprecedented level of precision in evaluating sperm morphology, motility, and function. This article presents a comprehensive and multidisciplinary review of AI applications in sperm analysis, spanning conventional methodologies and their limitations to advanced classification and predictive models. It also explores the integration of AI with "omics" technologies (genomics, transcriptomics, proteomics, and epigenomics), the development of microfluidic devices, and the adoption of big data techniques in clinical practice. The review concludes with a discussion on ethical considerations, the need for multicenter validation studies, and future advancements that could lead to a deeply personalized and equitable approach to reproductive medicine.

2. Introduction

2.1. The Challenge of Male Infertility in the 21st Century

The World Health Organization (WHO) estimates that approximately 15% of couples of reproductive age experience difficulties conceiving after one year of unprotected sexual intercourse [1]. Among these cases, around 40% are attributed to male factors, highlighting the importance of semen analysis and sperm quality assessment in the comprehensive evaluation of infertile couples [2]. While multiple factors can affect male fertility-ranging from hormonal, genetic, anatomical, and immunological to environmental influences-conventional sperm evaluation remains a cornerstone of the initial diagnostic approach.

2.2. Traditional Semen Analysis

In the late 20th century, WHO established parameters for semen analysis, encompassing variables such as volume, pH, concentration, motility, and morphology [3]. These criteria have been updated across several editions, reflecting advancements in reproductive science. The primary objective of these guidelines is to standardize laboratory practices, facilitate result comparisons, and support clinical research. However, despite standardized protocols, various factors-including subjectivity, observer fatigue, and differences in technical training-introduce variability and limitations in reproducibility [4].

2.3. Limitations of Conventional Methods

Despite its utility, conventional semen analysis presents several shortcomings:

1. Lack of objectivity: Morphological evaluation relies on microscopic observation and the classification of sperm cells as normal or abnormal based on morphological criteria (head size, acrosome, midpiece, and tail). This assessment is inherently influenced by the subjective judgment of the analyst [5].

2. Limited functional insight: Traditional analysis provides minimal information on sperm functionality, including DNA integrity, oxidative stress levels, and other molecular aspects critical to fertility.

3. Inter- and intra-observer variability: Manual assessments are prone to inconsistencies, leading to discrepancies between evaluations conducted by different professionals or even by the same analyst at different times.

4. Inability to integrate multi-omic data: Conventional methods do not incorporate genomic, transcriptomic, proteomic, or epigenetic data, which are crucial for understanding sperm function at a molecular level.These limitations underscore the need for more advanced methodologies that enhance diagnostic accuracy and predictive capabilities. In this context, artificial intelligence (AI) has emerged as a transformative tool, offering innovative solutions to overcome these challenges in male infertility assessment.

3. The Emergence of Artificial Intelligence in Reproductive Medicine

3.1. What is Artificial Intelligence?

Artificial intelligence (AI) encompasses a set of computational techniques that enable machines to perform tasks typically requiring human intelligence, such as reasoning, learning, perception, and decision-making [9]. Among its subfields, the most relevant include:

- Machine Learning (ML): Algorithms that learn from data and improve their performance with experience, without being explicitly programmed for each possible outcome.

- Deep Learning (DL): Based on deep neural networks with multiple layers, capable of recognizing complex patterns in large datasets.

- Computer Vision: Algorithms capable of processing and interpreting images or videos.

- Natural Language Processing (NLP): Focused on analyzing and generating human language (less directly applicable to semen evaluation but relevant

3.2. Applications in the Field of Assisted Reproduction

In reproductive medicine, AI has been applied to multiple areas: predicting ovarian response in IVF, embryo selection based on advanced algorithmic analysis, sperm quality assessment [10], and optimizing laboratory protocols for assisted reproduction techniques. AI-driven models enable more precise embryo grading by analyzing time-lapse imaging data, improving implantation success rates. Additionally, machine learning techniques assist in identifying sperm with the highest fertilization potential, thus refining the selection process for intracytoplasmic sperm injection (ICSI). These advancements contribute to increased success rates in fertility treatments, reduce subjectivity in clinical decisions, and pave the way for a more personalized approach to reproductive medicine.

Key factors driving the integration of AI in assisted reproduction include:

1. Capacity to handle large volumes of data: Assisted reproduction generates a vast number of clinical records, laboratory data, and imaging (microscopy, embryo time-lapse).

2. Need for precision: Small differences in the evaluation of reproductive cells (oocytes, spermatozoa, embryos) can significantly impact success rates.

3. Pursuit of objectivity: AI tools can reduce human variability, providing more reproducible diagnostics and prognostics.

3.3. AI as a Catalyst for Personalized Reproductive Medicine

Personalized medicine aims to tailor clinical interventions to the individual profile of each patient, considering not only their phenotypic traits but also their genetic and environmental background. In the field of male infertility, this involves integrating "omics" data (genomic, transcriptomic, proteomic, and epigenetic) alongside clinical and lifestyle parameters [11]. AI offers the opportunity to synthesize these massive and complex datasets, identifying correlations or patterns that may be imperceptible to the human eye, ultimately leading to customized treatment protocols.

Table 1

Criterion	Conventional Analysis	Al-Assisted Analysis
Objectivity	Highinter• andintra-observer variability, depends on the analyst'sskill.	Reduces subjectivity by applyingalgorithmstrainedwithstandardized databases.
Analysis Time	Takes longer, as the professionalmust manually count and individually assessmorphology.	Fast real-time (or nearreal-time) analysis, automated by computervision algorithms,

Costs and Equipment	Requireslesstechnological equipment (traditional microscope) but need strained personnel.	Higher initialinvestment (software, hardware), but lowers long-term costs due to speed and standardization.
Level of Detail	Focuseson basic parameters (concentration,motility, morphology), with limited molecular assessments,	Potential to integrate morphological and functionaldata (ONA fragmentation, epigenetics, etc.)
Big Data Integration Different type	Difficult to processlargevolumes of data manually.	Enables correlation of clinical,"omic,"and lifestyle information in complex predictive models.
Reproducibility	limited by subjectivity; results may vary between laboratories,	High reproducibility once the algorithmistrained and validated cross different populations,

4. Foundations of Sperm Evaluation and Modernization with AI

4.1. Count, Motility, and Morphology: The Traditional Basis

The basic WHO parameters for semen evaluation include:

- Volume: Normally between 1.4 and 1.7 ml after an abstinence period of 2-7 days.
- Concentration: A sperm counts above >16 million per ml is considered normal.
- Motility: Categorized as progressive, non-progressive, or immotile; progressive motility above >30% is associated with higher conception probabilities.
- Morphology: Percentage of sperm with normal shape according to strict criteria (Kruger or the latest WHO edition), ≥4% considering head, midpiece, and tail [12].

Each of these parameters provides relevant information, but individually they are insufficient to fully describe sperm functional complexity.

4.2. Advanced Functional Parameters

The evolution of andrology has focused on additional factors such as:

- DNA Fragmentation: Various techniques (TUNEL, SCSA, COMET) quantify DNA strand breaks in sperm, which are associated with lower embryo quality and implantation rates [13].
- Chromatin Status: Improper chromatin compaction can increase DNA susceptibility to oxidative damage.
- Epigenetic Markers: DNA methylation, histone modifications, and non-coding RNA presence can influence early embryonic reprogramming and have implications for offspring [14].
- Mitochondrial Quality: Since mitochondria supply the energy needed for motility, their integrity is closely linked to sperm function

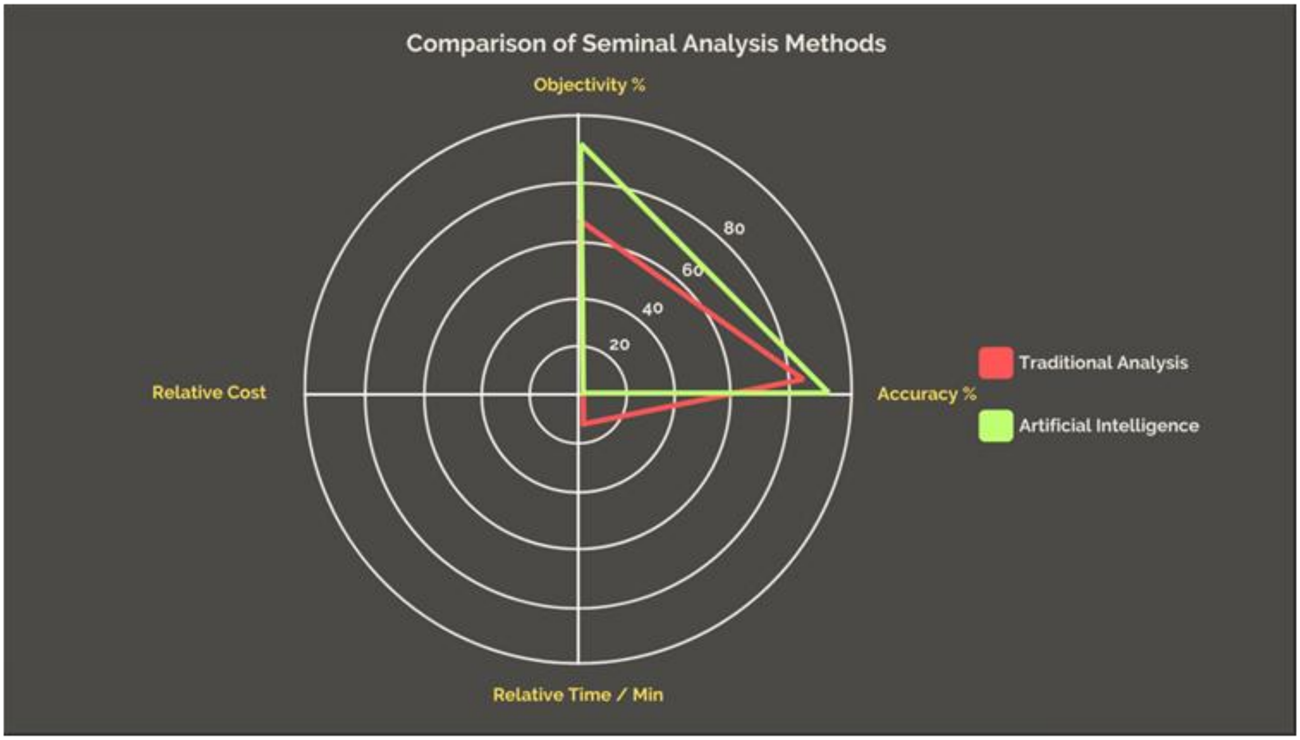
These advanced tests have significantly improved the understanding of male fertility but are often more expensive and complex, requiring highly specialized personnel. Here, AI can contribute through automated methods that not only quantify morphology and motility but also integrate molecular and functional readings into a robust system for predicting reproductive potential.

4.3. The Role of AI in Modernizing Semen Analysis

AI is integrated into sperm analysis primarily through Computer Vision and Deep Learning algorithms applied to images captured by conventional microscopes or digital video systems. These algorithms can:

1. Identify and segment spermatozoa: Differentiating sperm cells from white blood cells, epithelial cells, or other artifacts.
2. Quantify characteristics: Head length, width, elongation index, tail curvature, movement in x and y axes, displacement velocity, etc.
3. Classify sperm: Labeling sperm as normal or abnormal based on learned morphological criteria or predicting fertilization success probability based on patterns discovered by neural networks.

With a system trained on thousands or millions of expert-annotated samples, AI can replicate and, in many cases, surpass human diagnostic capabilities in specific aspects of sperm evaluation [15].



GRAPHIC 1:

5. Machine Learning and Deep Learning Techniques Applied to Sperm Analysis

5.1. Machine Learning: Concepts and Classical Models

Classical Machine Learning models (e.g., Decision Trees, Support Vector Machines (SVM), Random Forests) require manual feature extraction. In sperm analysis, an expert might define attributes such as head width, length-to-width ratio, midpiece asymmetry, among others. The algorithm then learns to associate these features with the target variable (e.g., normal/abnormal classification or presence/absence of DNA fragmentation).While these models can yield good results when features are well-defined, their performance largely depends on the expertise of the specialist selecting the variables and the proper preprocessing of data [16].

5.2. Deep Learning: The Revolution of Convolutional Neural Networks

In Deep Learning, particularly in Convolutional Neural Networks (CNNs), feature extraction is performed automatically through multiple convolutional layers. In broad terms:

1. Input Layer: Receives the original image of a sperm cell (or a cropped section containing it).
2. Convolutional and Pooling Layers: Apply filters to detect edges, textures, and morphological patterns.
3. Fully Connected Layers: Translate detected patterns into probabilities of belonging to certain classes (e.g., normal vs. abnormal sperm).
4. Output Layer: Provides the final classification or probability of certain characteristics (progressive motility, structural integrity, etc.) [17].

This approach has demonstrated exceptional ability to detect subtle anomalies in sperm shape or motility that might go unnoticed by the human eye. Moreover, the scalability and adaptability of neural networks enable continuous improvement as more data is incorporated.

Table 2:

Architecture	Description	Applications in SpermAnalysis
Convolutlonal Neural Networks (CNNs)	Use convolutionallayersto extract hierarchical image features (edges, textures, shapes).	Detection of morphological defects, classification of normal vs. abnormal sperm, automatic sperm counting.
Generative Adversarial Networks (GANs)	Consist of two competing networks (generator and discriminator) that create and validate synthetic images,	Generation of synthetic sperm images, expanding datasets for AI training and improving model robustness

Hybrid Hoclels (CNN+**RNN,**etc.)	Combine CNNs (for spatial features) with fRNNs (for temporal sequences) to analyze both morphology and movement patterns.	Real-time sperm motility analysis, dynamic tracking of sperm shape evolution.
Model Ensemble (e.g.,RandomForest+ CNN)	Integrates multiple models in parallel to improve accuracy by combining partial classifications into a final robust prediction.	Predictingclinicaloutcomes such as DNA fragmentation, fertility potential, or success rates in IVF/ICSI procedures,

5.3. Computer Vision for Motility Tracking

Computer Vision is also applied to the dynamic analysis of sperm motility. Individual tracking algorithms can record each sperm cell's trajectory in a video, calculate curvilinear velocity, displacement linearity, and flagellar beat frequency. Using this data,it is possible to classify motility types and estimate the probability of successful fertilization [18].A concrete example is the integration of optical flow algorithms, which estimate pixel displacement in video sequences, enabling the recognition of subtle movements. AI adds a layer of machine learning that classifies these movements as suitable or inadequate in reproductive terms.

6. New Perspectives: AI and Integrative Sperm Analysis

6.1. Integration of Omics Data

Sperm quality can also depend on genetic and epigenetic factors (e.g., point mutations, chromosomal rearrangements, DNA methylation, histone modifications, and non-coding RNA). With the decreasing costs of high-throughput sequencing (NGS), generating large volumes of “omics” data for each individual is becoming increasingly viable [19].AI can correlate these genomic and epigenomic data with traditional (motility, morphology) and functional indicators (DNA fragmentation, oxidative stress), building much more comprehensive predictive models. For example, algorithms have been developed that predict the risk of male infertility associated with specific genetic variants or abnormal methylation levels in key promoter regions [20].

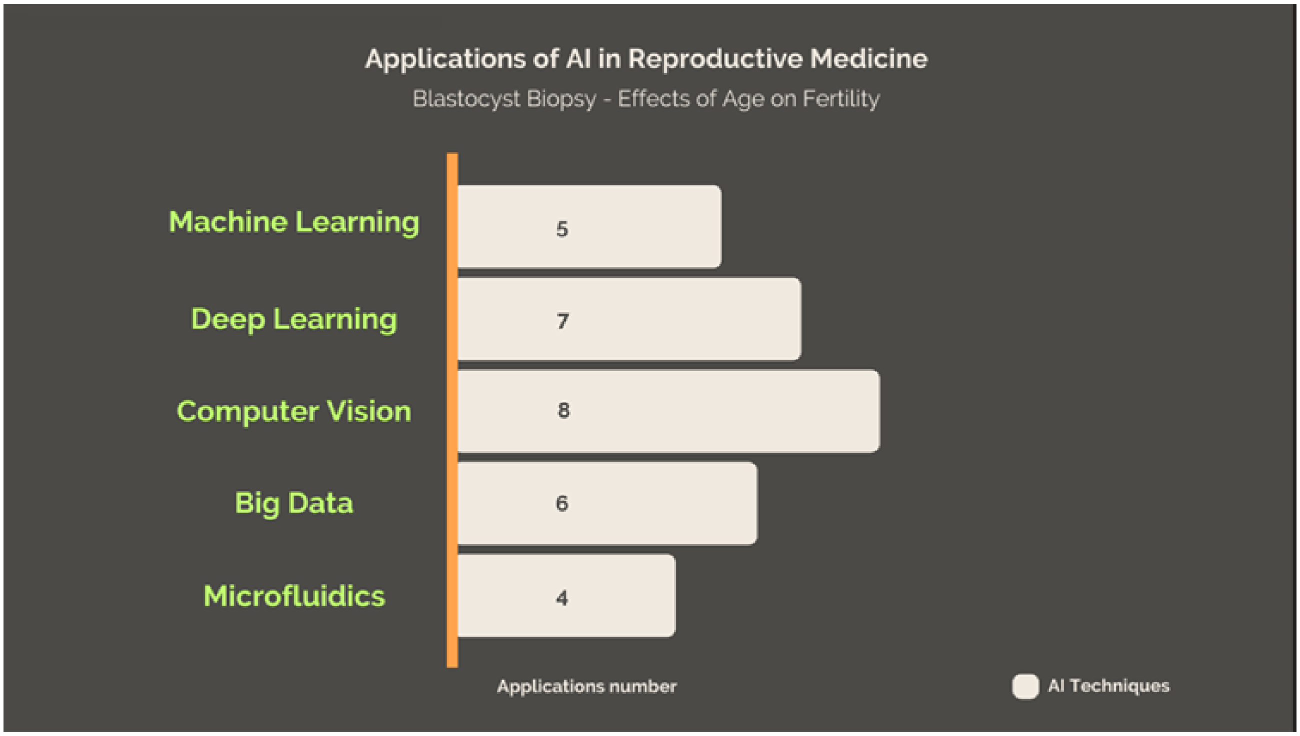
Moreover, integrating multi-omics data with AI facilitates the discovery of novel biomarkers for sperm quality and fertility potential. By leveraging systems biology approaches, AI can map interactions between genetic, epigenetic, proteomic, and metabolomic factors, providing a holistic perspective on sperm function. These models not only enhance diagnostics but also enable the development of targeted therapies and lifestyle recommendations to improve reproductive outcomes.Another key advantage of AI-driven multi-omics integration is its ability to personalize treatments. By analyzing a patient's unique omics profile, AI can help optimize assisted reproductive techniques (ART), guiding interventions such as sperm selection, embryo implantation timing, and hormonal therapies. This level of personalization could significantly improve ART success rates while reducing unnecessary interventions and costs.

6.2. Microfluidics and Intelligent Sperm Selection

Microfluidic technology is transforming the way sperm processing and selection are performed. Devices known as “lab on a chip” enable the passive separation (without centrifugation) of sperm with better motility and lower DNA fragmentation [21]. When these systems are combined with sensors and AI algorithms, they can monitor, in real-time, cell displacement capacity and morphology, automatically selecting gametes with the highest probability of fertilizing an oocyte.This process not only reduces analysis time and laboratory handling but also minimizes damage associated with traditional semen processing techniques (density gradients, repeated centrifugations), leading to lower production of reactive oxygen species (ROS) and reduced DNA fragmentation [22].Moreover, AI-powered microfluidic platforms can integrate additional data sources, such as sperm mitochondrial activity and epigenetic markers, to further refine selection criteria. These advancements pave the way for non-invasive, highly efficient sperm selection methodologies that align with precision medicine in reproductive health.

6.3. Prediction of Success in Assisted Reproductive Procedures

A central objective in andrology and reproductive medicine is predicting the success of assisted reproductive techniques (ART), such as in vitro fertilization (IVF) or intracytoplasmic sperm injection (ICSI). AI can integrate male factors (semen parameters, genomic data, hormone levels, lifestyle), female factors (age, ovarian reserve, uterine conditions), and embryonic factors (embryo morphology, division kinetics) to estimate implantation probability and live birth rates [23].Several studies have demonstrated that machine learning models outperform traditional statistical methods in predicting clinical outcomes, particularly when handling large datasets with numerous predictors. This predictive approach helps embryologists design protocols, provide more accurate prognoses to couples, and optimize resource utilization in fertility clinics.



GRAPHIC 2:

7. Personalized Reproductive Medicine: An AI-Based Approach

7.1. Concept of Personalized Medicine

Personalized (or precision) medicine is based on the premise that each individual possesses a unique profile determined by their genome, epigenome, and environment. In assisted reproduction, tailoring interventions to this profile can significantly improve clinical outcomes[24]. In the case of male infertility, this implies:

- More specific diagnoses regarding the origin of the problem (genetic, epigenetic, anatomical, environmental, hormonal, etc.).
- Individualized treatment selection (e.g., use of ICSI in cases of severe teratozoospermia or conventional IVF in cases with altered male factor).
- Personalized recommendations for nutrition, antioxidant supplementation, lifestyle modifications (reducing tobacco, alcohol, and stress), and addressing co-factors (such as varicocele correction).

By leveraging AI, clinicians can integrate a patient's multi-omics data, semen parameters, and clinical history to generate tailored reproductive strategies. This holistic approach maximizes the likelihood of successful conception while minimizing unnecessary interventions.

7.2. AI as a Tool for Patient Classification

One of the most notable benefits of AI is its ability to group or classify patients according to underlying patterns that may not always be evident to clinicians [25]. For instance, patients with similar genomic profiles may share specific reproductive characteristics, risk factors, or responses to treatment.AI-based clustering techniques, such as unsupervised learning algorithms, can segment patients into subgroups based on multi-omic data, hormonal levels, lifestyle factors, and past reproductive history. This classification aids in:

- Personalized treatment plans: Tailoring interventions based on genetic and molecular biomarkers.
- Risk stratification: Identifying patients who may require more intensive monitoring or alternative therapeutic approaches.
- Optimization of ART protocols: Adjusting fertility treatments, such as embryo transfer strategies, based on predicted success rates.

By leveraging AI for patient classification, clinicians can move towards truly individualized reproductive care, maximizing treatment efficacy while reducing unnecessary interventions.

7.3. Dose Adjustment and Stimulation Protocols

In assisted reproductive treatments, optimizing the ovarian stimulation protocol can influence oocyte synchronization with sperm quality. Although this is traditionally a female factor, AI could correlate semen quality (in its various parameters) with the partner's response to stimulation and predict the optimal timing for oocyte retrieval [26]. This approach turns personalized reproductive medicine into a truly systemic strategy, where both male and female factors are integrated into a global predictive model.

8. Recent Advances and Innovation Areas in AI and Sperm Analysis

8.1. High-Resolution Systems and Advanced Microscopy

The incorporation of high-resolution microscopy techniques (e.g., confocal microscopy or holographic microscopy) offers new insights into sperm analysis. When combined with AI, these technologies can extract detailed features of the head (acrosomal structure, nuclear vacuoles), midpiece (mitochondrial distribution), and tail (curvatures or anatomical defects) [27]. These improvements enable more precise diagnoses while reducing the need for invasive staining or prolonged laboratory procedures.

8.2. Generative Networks and Data Augmentation

Generative Adversarial Networks (GANs) are not only capable of generating synthetic sperm images but can also enhance the quality of images captured under suboptimal conditions [28]. These techniques expand training datasets for classification algorithms, reducing overfitting and improving model robustness in heterogeneous clinical environments.

8.3. Telemedicine and Self-Diagnosis

The rise of telemedicine has driven the development of portable devices that, when coupled with smartphone cameras, allow for preliminary at-home semen analysis [29]. AI algorithms process the images and provide basic indicators of concentration and motility. While this approach does not replace laboratory evaluation, it can serve as a screening tool or aid in monitoring treatments, reducing the need for patient travel.

8.4. Integration with Robotics in Embryology Laboratories

The automation of processes in in vitro fertilization (IVF) laboratories is progressing alongside AI advancements. From robotic systems that handle microdoses of semen and culture media to semi-automated tools that precisely insert the selected sperm into the oocyte (robot-assisted ICSI) [30], these technologies aim to reduce human variability, minimize errors, and ultimately improve fertilization success rates.By integrating AI with robotics, IVF laboratories can enhance procedural standardization, optimize sperm selection, and refine embryo culture conditions. These innovations represent a step toward fully automated reproductive technologies that may further increase efficiency and accessibility in fertility treatments.

9. Ethical Considerations and Implementation Challenges

9.1. Privacy and Data Protection

AI requires large volumes of data (clinical, genomic, imaging), raising concerns about confidentiality and personal information security. Regulations such as the General Data Protection Regulation (GDPR) in the European Union impose strict requirements on the collection, storage, and processing of sensitive data [31]. Given the inherently confidential nature of reproductive medicine, robust privacy and cybersecurity protocols must be implemented to protect patient information.

9.2. Clinical Acceptance and Trust in the “Black Box”

While AI offers undeniable benefits, interpreting outputs from deep neural networks can be challenging for end-users (physicians, embryologists, patients). This phenomenon, known as the “black box” problem, raises concerns about accountability in diagnostic errors and the ability to explain why the system recommends a specific course of action[32]. The current trend in medical AI is toward explainable AI (XAI), which seeks to provide clear, interpretable justifications for its decisions, fostering greater trust and clinical adoption.

9.3. Technological Gap and Equity in Access

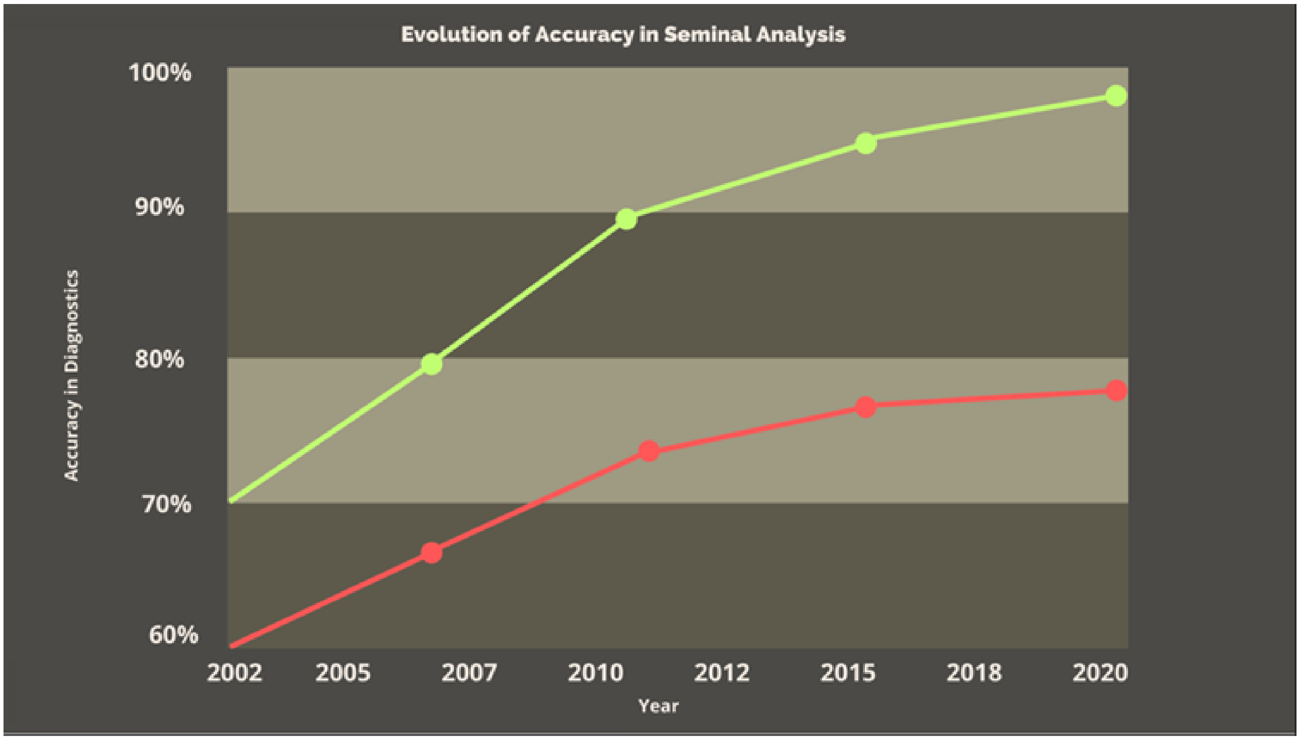
The implementation of AI-driven systems and high-end equipment could widen the gap between fertility clinics in developed countries and those in resource-limited settings[33]. Ensuring that these innovations benefit populations equitably requires strategic health policies, adequate funding, and professional training in regions where digital infrastructure may be limited. Bridging this technological divide is crucial to making AI-driven reproductive medicine accessible on a global scale.

9.4. Multicenter Validations and Standardization

For AI to be solidly integrated into clinical practice, multicenter studies are required to validate the efficacy and reproducibility of algorithms across different populations, laboratories, and sampling conditions [34]. Additionally, standardized protocols must be established through consensus by scientific societies, such as the European Society of Human Reproduction and Embryology (ESHRE) and the American Society for Reproductive Medicine (ASRM), to evaluate and certify these technological tools. The development of unified guidelines will not only ensure the reliability of AI-based sperm analysis but also promote regulatory compliance and facilitate its adoption in diverse clinical settings.

10. Discussion: Clinical Implications and Future Projections

AI has demonstrated its potential to enhance the precision of sperm evaluation, reducing the subjectivity inherent to human observation and enabling a more comprehensive analysis of gamete functionality. By combining Computer Vision techniques with Deep Learning algorithms, more accurate diagnostics, early detection of subtle anomalies, and the development of individualized therapeutic plans become feasible [35].However, the path toward full AI adoption in reproductive medicine is not without challenges. Data heterogeneity, international regulatory fragmentation, and the complexity of algorithmic models pose significant hurdles. Nonetheless, the potential benefits-both economic and in terms of clinical outcomes-are highly appealing. Reducing failed IVF cycles, lowering costs associated with repetitive procedures, and increasing successful pregnancy rates translate into enhanced well-being for infertile couples and optimized healthcare resource allocation [36].Similarly, personalized reproductive medicine could become the new standard in the medium term. AI tools capable of integrating genomic, epigenetic, and clinical data may more accurately predict embryo development and even guide medical teams in selecting surgical or pharmacological strategies. For example, in cases where the male factor predominates, AI-driven protocols could propose pre-treatment interventions to improve sperm quality before initiating assisted reproductive treatments (e.g., dietary changes, antioxidant supplementation, and modification of harmful lifestyle habits) [37].Furthermore, future advancements in robotic systems and the increasing sophistication of microfluidic devices could drive andrology and embryology laboratories toward highly automated environments. In such a scenario, human intervention would focus on supervision, comprehensive result interpretation, and patient interaction, while screening and cell selection tasks would be largely managed by AI [38].



GRAPHIC 3:

11. Conclusions

The integration of artificial intelligence (AI) into sperm analysis and reproductive medicine marks the beginning of a new era in precision diagnostics and personalized treatments. This convergence between advanced computational models and reproductive biology is redefining standards, optimizing laboratory processes, and expanding the horizons of reproductive science. The key takeaways from this transformative landscape are:

1. AI revolutionizes sperm evaluation: By providing objectivity and speed in detecting morphological and functional alterations, AI reduces variability and facilitates the standardization of results, overcoming the subjectivity of traditional assessments.
2. Integration of advanced data sources: AI enables the combination of multiple data streams—including genomic, epigenetic, and environmental factors-to construct predictive models with unprecedented accuracy, laying the groundwork for true precision reproductive medicine.
3. Personalization of treatments: The synergy between AI and emerging "omics" technologies allows for tailored reproductive strategies, optimizing ovarian stimulation protocols and selecting fertilization techniques based on each patient's unique reproductive profile.
4. Automation of reproductive laboratories: The development of robotic systems, computer vision techniques, and microfluidic platforms powered by AI-driven algorithms is paving the way for highly automated, efficient, and standardized assisted reproduction laboratories.
5. Ethical and regulatory challenges: Despite these advances, the responsible implementation of AI requires a robust ethical and legal framework that ensures patient privacy, equitable access to technology, and algorithmic transparency to prevent biases and enhance trust.

In summary, the fusion of artificial intelligence with andrology and reproductive medicine represents a paradigm shift that extends beyond improving success rates in fertility treatments. It deepens our understanding of sperm biology, refines diagnostic accuracy, and enhances therapeutic precision. While significant challenges remain, the potential to deliver more accurate diagnoses, more effective treatments, and a more patient-centered approach positions AI as an indispensable ally in the fight against male infertility and the pursuit of successful conception. The future of reproductive medicine is being reshaped, and AI stands at the forefront, not only as a tool but as a transformative force driving the next generation of fertility care.

References

1. Zegers-Hochschild F, Adamson GD, de Mouzon J. International Committee for Monitoring Assisted Reproductive Technology (ICMART) and the World Health Organization (WHO) Revised Glossary on ART Terminology. Hum Reprod. 2009;24(11):2683-2687.
2. Winters BR, Walsh TJ. The epidemiology of male infertility. Urol Clin North Am. 2014;41(1):195-204.
3. World Health Organization. WHO Laboratory Manual for the Examination and Processing of Human Semen. 6th ed. Geneva: WHO. 2021.
4. Cooper TG, Noonan E, von Eckardstein S. World Health Organization reference values for human semen characteristics. Hum Reprod Update. 2010;16(3):231-245.
5. Menkveld R, Wong WY, Lombard CJ. Semen parameters, including WHO and strict criteria morphology, in a fertile and subfertile population: an African perspective. Hum Reprod. 2001;16(6):1165-1171.
6. Agarwal A, Durairajanayagam D, Halabi J, Peng J, Ramos L. Proteomics, oxidative stress and male infertility. Reprod Biomed Online. 2014;29(1):32-58.
7. Jurewicz J, Radwan M, Sobala W. Lifestyle and semen quality: role of modifiable risk factors. Syst Biol Reprod Med. 2014;60(1):43-51.
8. Krausz C, Riera-Escamilla A. Genetics of male infertility. Nat Rev Urol. 2018;15(6):369-384.
9. Russell S, Norvig P. Artificial Intelligence: A Modern Approach. 4th ed. Upper Saddle River: Prentice Hall. 2021.
10. Johnson MH. The application of artificial intelligence techniques to assisted reproduction. Hum Reprod. 2019;34(7):1161-1164.
11. Venter JC, Adams MD, Myers EW. The Sequence of the Human Genome. Science. 2001;291(5507):1304-1351.
12. Kruger TF, Acosta AA, Simmons KF. new method of evaluating sperm morphology with predictive value for human in vitro fertilization. Urology. 1987;30(3):248-251.
13. Sakkas D, Alvarez JG. Sperm DNA fragmentation: mechanisms of origin, impact on reproductive outcome, and analysis. Fertil Steril.2010;93(4):1027-1036.
14. Carrell DT. Epigenetics of the male gamete. Fertil Steril. 2012;97(2):267-274.
15. Kovacs E, Habertheuer A, Strohmer B. A deep learning approach for the morphological assessment of human sperm heads. Sci Rep. 2020;10(1):16575.
16. Li H, Zhao Y, He R. Deep learning-based identification of human sperm heads: an automatic morphological classification for in vitro fertilization. Comput Methods Programs Biomed. 2021;209:106318.
17. LeCun Y, Bengio Y, Hinton G. Deep learning. Nature. 2015;521(7553):436-444.
18. Connover H, Hogges J, Tamer A, Zeidner L. Automated tracking of sperm motility using deep learning. Fertil Steril. 2020;114(3): e305.
19. Jenkins TG, Aston KI, Pflueger C, Cairns BR, Carrell DT. De novo mutations, paternally derived structural rearrangements, and male infertility. Fertil Steril. 2017;107(4):880-886.
20. Cheung S, Schroeder B, Myer EN, Tannenbaum S, Ginsburg ES, Boulos A. Machine learning to predict live birth outcomes in in vitro fertilization. Fertil Steril.2020;113(6):1124-1132.
21. Quinn MM, Jalalian L, Ribeiro S. Microfluidic sorting selects sperm for clinical use with reduced DNA damage compared to density gradient centrifugation. Andrology. 2018;6(4):715-722.
22. Ainsworth C, Nixon B, Aitken RJ. Development of a novel electrophoretic system for the isolation of human spermatozoa. Hum Reprod. 2011;26(5):1116-1128.
23. Polanski LT, Baumgarten MN, Quenby S. What exactly do we mean by ‘personalized medicine’ in reproductive medicine? A systematic review and meta-analysis. Reprod Biomed Online. 2014;28(3):366-379.
24. Schlegel PN, Sigman M, Collura B. Diagnosis and treatment of infertility in men: AUA/ASRM Guideline. J Urol. 2021;205(1):36-43.
25. Wang R, Newcomb RG, Lam WA. Understanding the Approaches and the Challenges of AI in Reproductive Medicine. Fertil Steril. 2021;116(4):813-821.
26. Boivin J, Griffiths E, Venetis CA. Emotional distress in infertile women and failure of assisted reproductive technologies: meta-analysis of prospective psychosocialstudies. BMJ. 2011;342:d223.
27. Abdelmoula WM, Galli R, Pais RC. Automated 3D segmentation of microparticles by integrating deep learning classification with watershed detection. Cytometry A. 2018;93(11):1102-1110.
28. Goodfellow I, Pouget-Abadie J, Mirza M. Generative Adversarial Networks. Commun ACM. 2020;63(11):139-144.
29. Kanakasabapathy MK, Sadasivam M, Singh A. An automated semen analysis platform integrating smartphone-based microscopy, machine learning, and IoT for remote male infertility diagnosis. PLoS One. 2017;12(5):e0177780.
30. Meseguer M, Kruhne U, Laursen S. Full in vitro fertilization laboratory mechanization: towards robotic assisted reproduction? Reprod Biomed Online. 2012;24(4):379-386.
31. Regulation (EU) 2016/679 of the European Parliament and of the Council (GDPR). Official Journal of the European Union. 2016;119(1):1-88.
32. Kundu S. AI in medicine must be explainable. Nat Med. 2021;27(8):1328.

33. Mathur R, Smith A, Khoury MJ. Equitable AI for global health: from design to deployment. Lancet Digit Health. 2021;3(2):e70-e72.
34. Esteva A, Robicquet A, Ramsundar B. A guide to deep learning in healthcare. Nat Med. 2019;25(1):24-29.
35. Thakur A, Yadav YK, Kumar A. Automated sperm morphology classification using deep convolutional neural networks. Andrology. 2020;8(4):845-851.
36. Practice Committee of the American Society for Reproductive Medicine. Diagnostic evaluation of the infertile male: a committee opinion. Fertil Steril. 2020;115(1):46-54.
37. Esteves SC, Zini A, Aziz N. Critical appraisal of WHO's new reference values for human semen characteristics. Urology. 2012;79(1):16-22.
38. Esteves SC, Varghese AC, Agarwal A, eds. Automation and Robotics in Andrology and Embryology. New York: Springer. 2022.