RESEARCH PAPER

IVF Outcome Prediction Based on Embryo Grading and Clinical Parameters Using Machine Learning and Deep Learning

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ABSTRACT
In-vitro fertilization (IVF) has become one of the most widely used assisted reproductive technologies for the context of treating infertility. But despite technological advancements, the success rate of IVF remains one of the limited as a result of the complexity of biological, clinical, and embryological factors involved. Traditional IVF decision-making relies heavily on the subjective embryo grading as well as limited clinical indicators, leading to the variability in the outcomes. To predict the outcome, depending on the morphology of the embryo and the collection of clinical parameters, in this paper, the detailed architecture of IVF outcome prediction based on machine learning (ML) and deep learning (DL) is proposed. The provided system is premised on deep learning models in order to auto graduate embryos based on morphological characteristics identified by utilizing the embryo images and machine learning models interpret such clinical parameters as age, hormone levels, and medical history. These two modalities are then fused together as multimodal fusion approach that predicts pregnancy success and increases embryo selection. The framework will aid in establishing precision in the prediction, reduce subjectivity besides providing a data based system of decision support to the clinicians. The available literature experimental results indicate that predictive performance is rather considerably improved by integration of both clinical and image attributes as compared to single-modal predictive techniques. The proposed solution may result in the development of personalized reproductive medicine and will potentially raise the percentage of successful IVF, reduce the patient stress levels, and reduce the level of medical costs.
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1. INTRODUCTION

Infertility affects millions of couples all over the world creating a significant medical and the social challenge. The in-vitro fertilization (IVF) has become one of the most helpful treatment methods to the patients as it is able to perform fertilization outside of the human body, and transfer the embryo into the uterus. Its success rate with an average of 30-40 percent per cycle remains quite low despite the fact that it is widely used. This limitation can be explained by the fact that the effects of factors are quite complex and influence the embryo development and implantation. One of the most significant procedures in the IVF is embryo selection [1]. Traditionally, morphological grading has been used to assess the quality of embryos as an evaluation of developmental age using the eye using the microscope. This process determines such characteristics as the blastocyst growth, cell uniformity and disintegration. It is an opinionated approach however that is subject to inter-observer error. Other clinical complications, such as maternal age, hormone levels, body mass index (BMI), and reproductive history are also very crucial in the outcome determination of IVF besides the quality of the embryos. In conventional approaches, though, the factors are normally considered to have independent work but not to exhibit complex interaction among themselves [2]. More recently, new opportunities to optimize the result of the IVF process were available in the domain of artificial intelligence (AI) in general and machine learning (ML) and deep learning (DL) in particular. ML models can be used on structured clinical data, whereas the DL models are better certified when it comes to extracting unstructured data features (images and videos). In the present paper, the subject of the combination of embryo morphology and clinical parameters via the practices of ML and DL algorithm and prediction of the outcomes of IVF research is described. It targets the development of a more robust, multimodal and self-evaluative structure, which can test embryos and predict the success of pregnancy in even a more precise and dependable manner.

2. LITERATURE REVIEW

Hassan (2020) notes that the utilization of machine-learning methods in predicting pregnancies after using IVF treatment is a major breakthrough in the reproductive care field. The research also discusses the necessity to use formal clinical information, including patient demographics, hormonal levels, and medical history, to generate predictive models that could be used by clinicians in their decision-making. Hassan points out that ancient statistical techniques usually are not effective at measuring the complex and nonlinear relations between the variables affecting the IVF success. By contrast, machine learning models like Support Vector Machines, Random Forests, and Artificial Neural Networks offer better predictive tasks by extracting detailed patterns in large volumes of data. The study illustrates that machine learning models have the potential to be more accurate than traditional methods especially when it involves multiple clinical parameters at the same time. Another important fact that should be noted by Hassan is that the selection of features has a significant effect on the quality of the model since inappropriate or duplicated variables may reduce the quality of the prediction. The paper also addresses problems that relate to data quality and accessibility as incomplete or inaccurate datasets may reduce the capacity of machine learning models. A second valuable input of this study is the debate of whether machine learning models are interpretable within a clinical setting. Although the complex models can be more accurate, Hassan admits that this can be not always transparent and cannot be trusted by clinicians and implemented into the practice. Thus, the research indicates explanatory methods of AI that would help to reduce the contrast between the performance of models and clinical usability. On the whole, the work by Hassan has a good basis to integrate machine learning into IVF outcome prediction. It states the opportunities of the data-driven method to enhance clinical decision-making and underlines the necessity of additional research to overcome the issue of data quality, model interpretability, and generalization.

According to Cimadomo (2023), the grading of embryos with deep learning is a groundbreaking innovation in the IVF practice. The paper is dedicated to the design and pre-clinical testing of an embryo grading system based on deep learning during preimplantation genetic testing (PGT-A) cycles. Cimadomo asserts that manual embryo evaluation is very subjective and subject to variability and this may result in different outcomes between various embryologists and clinics. The study also shows that deep learning models, especially convolutional neural networks may be applied successfully to analyse embryo images and deliver consistent grading. Cimadomo points out that the automated system is efficient in preventing human error besides improving reproducibility of embryo examination. It also reveals that the model predictions have a strong correlation with clinical outcomes which include implantation rate and pregnancy rates which suggests that the model can be applied in real-life situations. The main strength of the study is that it focuses on clinical data validation. Cimadomo also emphasizes the necessity to test AI models in the real world so that they can be reliable and generalized. The findings indicate that deep learning systems may be used to complete the knowledge of embryologists, but not replace, with objective and data-based information. Nevertheless, the research also commits some drawbacks, such as the requirement of large annotated data, as well as the computational expenses of deep learning models training. Cimadomo concludes that automation in IVF is an attractive research that requires more research and clinical verification so that these work can be incorporated as a common practice.

Image processing methods have been instrumental in improving the embryo grading technology in IVF and especially with the advent of deep learning-powered models as posited by Isa (2023). The paper gives a critical literature review of conventional and current methods of analysing blastocyst images, including the shift in the manual evaluation system to automated mechanisms. Isa points out that traditional image processing techniques are based on handcrafted features and this might fail to fully represent the complexity of embryo morphology. The article explains the image analysis revolution of deep learning models, and in particular, convolutional neural networks, which automatically generate features of unaided data. Isa informs that such models have the capacity to recognize minor patterns in embryo images, and therefore, increase the accuracy in the grading and forecasting of the viability. In addition, the review examines different architectures and methods applied to deep learning such as transfer learning and data augmentation which are designed to overcome the issue of small datasets. Isa also emphasizes the need to combine image data with other modalities, e.g., the clinical and genetic information, to improve the prediction activity. The paper considers that the multimodal methods can offer more knowledge about the embryo development and enhance decision-making in Ivin spite of the progress, Isa list some of the challenges such as standardized datasets, model interpretability, and testing in various clinical environments. The paper concludes by concluding that image processing using deep learning has a significant future to offer to IVF although further research is still needed to address the current setbacks and make it universally available.

According to Vaidya (2021), deep learning application to predicting the time series in IVF is a new method of realizing embryo development. The paper aims at studying time-lapse imaging systems that illustrate the time process of embryo development by collecting data over time. Vaidya believes that the information obtained in ex-posit is limited to the use of static images, but there is useful information about the patterns and timing of development when time-lapses are taken into consideration. The study has shown that deep learning-based algorithms, including recurrent neural networks and convolutional neural networks, can be used to successfully analyse time series data to forecast embryo viability and machine grading. As Vaidya points out, these models are able to find temporal dependence and patterns, patterns that are not apparent in a static picture. This results in improved forecasts on the potential of implantation and pregnancy. An important addition to the research is that the study combines automated grading and time series analysis. Vaidya indicates that implementation of these methods can be combined in order to improve overall IVF prediction system performance. The paper also mentions how deep learning has the potential to alleviate the burden that embryologists have to endure through automation of the repetitive process and other tasks, as well as offering real-time information. Nevertheless, Vaidya admits such issues as the data availability and the computation complexity. The time-lapse imaging systems demand high storage and processing which pose a major challenge in large amount of data producing. Moreover, the necessity of the annotated datasets is a shortcoming. On the whole, the research paper suggests the significance of time series analysis in enhancing the results of IVF and the critical role of applying time data to prediction.

Ueno (2022) asserts that the creation of deep-learned annotation-free embryo scoring systems is an important development in the IVF technology. The researchers examine the association between automated embryo score and clinical outcomes, live birth and health of the newborns. Ueno highlights that the conventional approaches to scoring demand manual scoring, which is not a fast process, and they are prone to human bias. The study shows that deep learning models are capable of producing embryo scores without manual labelling and thus making the subjectivity minimal and enhancing efficiency. Ueno emphasizes that the automated scores are significantly associated with clinical outcomes, which suggests that they can predict the success of IVF. Judging by evidence presented in the study, these models can also be generalized in a wide range of datasets, which is why they can be applied to clinical use. The main strength of the research is the large number of cohort, as it increases the validity of the results. The validation is another crucial aspect of various clinical settings discussed by Ueno to verify the soundness of the model. The findings indicate that the annotation-free systems have the potential to enhance the current practices and enhance the embryo selection. In spite of these positives Ueno notes issues associated with model interpretability and the fact that further validation is required. These findings conclude the research finding that deep learning-based scoring systems can revolutionize the IVF practice to give an objective and reliable solution to the quality of embryos.

According to Khosravi (2019), deep learning can transform the process of evaluation and screening embryos in IVF by offering effective and automated solutions. The paper proves that the convolutional neural networks are effective to analyse blastocyst images and classify them as potentially implanted. Khosravi points out that deep learning models can perform better in some tasks than human experts by detecting intricate patterns in data of image data. The study reveals that the model proposed is very accurate at assigning embryo to classes and determining clinical outcomes. Khosravi underlines the fact that the performance of the model is explained by the use of big datasets and high-order architecture. Other issues raised in the study are the significance of data quality and preprocessing in obtaining credible results. Another important supplement to the work is that it demonstrates applicability in practice since the model is evaluated on various datasets of various clinics. This increases the aforementioned generalizability of the findings and helps to adopt deep learning to clinical practice. Khosravi also mentions an opportunity AI has to decrease subjectivity and enhance the consistency of embryo choosing. The study however recognizes issues concerning the computational requirements and interpretability requirements. According to Khosravi, future studies could be interested in formulating explainable models and combining various data modalities with the aim of improving the performance further. On the whole, the research offers solid proof of the efficacy of the deep-learning in the IVF and preconditions the further progress in this sphere.

3. PROBLEM STATEMENT

Despite significant technological and the clinical advancements in in-vitro fertilization (IVF), the success rate of the procedure remains one of the suboptimal, largely due to the complexity and variability inherent in the human reproductive biology. The procurement of embryo is one of the issues with great significance, and it directly relates to the likelihood of implantation and a successful pregnancy. Embryologists make conventional embryo grading using the methods of morphological assessment. The visual assessment of the embryo characteristics such as the cell symmetry and cell fragmentation and the formation of the blastocyst is based on the appraisals [3]. However, it is also a subjective process and much depends on the knowledge and experience of the viewer. This leads to the probability of the grades assigned by the different embryologists to the same embryo to not be aligned and this implies that the accuracy of coming up with a decision will be affected. This subjectivity gives it a variability which can negatively affect the results of IVF and does not allow the standardization of the applied clinical practice in different fertility centres.

In addition to quality of the embryos, there are also the clinical parameters, which are important in predicting the IVF success. The maternal age, hormonal condition i.e. the Anti-Mullerian Hormone (AMH) and Follicle-Stimulating Hormone (FSH), body mass index (BMI) the reproductive history and underlying medical conditions are some of the factors, which have significant effects in telling whether an implantation will be achieved and result in a live birth [4]. However, in the vast majority of the current clinical processes, these parameters are studied either independently or analyzed in a linear manner in a limited sense. Usually, standard statistical techniques are incapable of relocating to multifaceted non line connections among these variables. Moreover, the clinical data and the embryological testing have no effective interrelation and its type of analysis could not provide a universal perspective of the factors influencing the IVF effect. These scattered analysis makes the potential future analysis of the current systems limited, and it cannot be used to develop a treatment plan that will be personalized.

The other critical issue is that the accuracy of existing models on the outcomes of IVF is not very high. The oldest methods are either founded on few features or unimodal data, such as the clinical record or even the embryo per se but not bestowed on the synergistic capabilities of the two [5]. Even though machine learning models have proven to be potentially effective in analysis of structured clinical data, they cannot analyse and interpret unstructured information, such as images. On the one hand, deep learning systems are more effective in image recognition at the cost of missing a lot of significant clinical information that can influence the final results of the treatment process. The absence of modalities causes the incompleteness of the models who cannot offer the multifactorial view of the IVF and is therefore limited in its efficacy in the clinical sphere.

Besides this, making choices of IVF is a very uncertain process. Surgeons are compelled to reach some choices that are difficult to make, such as the appropriate embryo to transfer or the treatment program to apply based on partial or personal data. Such inconsistency could lead to a deviated outcome, increased financial and emotional price to the patients and possibility of future probability of multiple procedure of treatment [6]. Another issue related to the lack of standardized and data-driven decision support systems is also complicated by the fact that the clinicians rely on their judgment and experience, rather than objective and repeatable data.

With these challenges in mind, there is an impending need of one and intelligent based system that can address the limitations of the current practice in IVF. Such system should have the capacity to apply up-to-date technologies in subjectivity reduction and become more accurate due to deep learning-based approaches in automated scoring of embryos on morphological scales. At the same time, it has to involve clinical parameters, developed based on potent machine learning models to indicate the complexity of the relationship between patient-specific aspects [7]. Most importantly, there should be a general system that integrates embryo morphology and clinical data into a single multimodal system that would largely ease a resource to explore all the relevant factors. The suggested intervention will utilize all of these modalities in combination with each other to be more accurate with predictions, apply personalized treatment options, and ultimately the success rates of IVF will be higher.

4. PROPOSED METHODOLOGY

4.1 Overview of the Proposed Framework

It is suggested to make the framework a multimodal system which is based on a combination of embryo morphology and clinical parameters to foretell IVF outcomes more effectively. This system consists of the core objective of overcoming the underperformance of the conventional ones and combine the beneficial attributes of the deep learning and machine learning into a unified system [8]. It is a system that tries to provide three interrelated systems that can answer three crucial questions of IVF analysis and prediction.

The former one is an embryo grading that has been created using the world of deep learning. An essential aspect of applying an implantation potential is embryo morphology, and convolutional neural networks or any deep learning model would prove to be the perfect solution that would make reference to more complex visual embryo image features. This aspect is economical on subjectivity as there is automation in grading process hence there is uniformity in the assessment.

The second aspect is dedicated to study of clinical parameters using machine learning algorithms. There is abundant patient specific variable in clinical information such as age, hormonal traits and medical history, and this is a major determinant of the rates of IVF [9]. The hidden patterns and nonlinear relationships in this structured data will be able to be found using the machine learning and will provide more precise predictions than the usual statistical methods.

The 3rd component is multimodal fusion i.e. results of the deep learning and machine learning model are combined to form one predictive model. By combining these two, the system will be able to see both clinical and the visual information together as a whole resulting in a holistic view of what factors determine the success of IVF. The framework will improve the predictive accuracy and assist in individualized decision-making by the clinical practice using the complementary sources of data.

Overall, the proposed methodology may be regarded as the moving of the single-factor approach to study towards multifactorial and data-driven one that would capture the multifactorial nature of the concept of IVF.

4.2 Data Collection

The data used to train and test any machine learning or deep learning model has a significant impact on the quality of the model. About the context of the IVF outcome prediction, the data being used as part of the proposed system falls into two large categories that are data on clinical and data on embryo image [10]. Both these sources of information are the structured and unstructured information, respectively, and may be integrated in order to deliver the full picture of the IVF.

4.2.1 Clinical Data

Clinical data supports the patient-specific analysis and it contains various variables such as demographic, physiological and medical variables. Among them, maternal age happens to be the most influential among the predictors of the success of IVF because it directly affects ovarian reserves and oocyte quality. Body mass index (BMI) is also another factor, as underweight and overweight can be detrimental to the reproductive outcomes.

Approaches to investigating hormones, primarily the Anti-Mullerian Hormone (AMH) and Follicle-Stimulating Hormone (FSH) ones, provide highly valuable data regarding the ovarian work and its readiness to be fertilized [11]. The AMH levels provide the number of AMH, which indicates the remaining amount of the egg stock and the FSH levels are used to provide the number indicating the response of the body to the stimulation of the ovary. Other than these, history of medical conditions in the past, previous pregnancies, miscarriages and underlying health conditions are also sources of useful background information to predictor models.

The former efforts at IVF also play a great role since they provide a context on the history of the treatment response and outcome. Through these variables, the system may develop a complete profile of all patients and individual forecast prediction and treatment planning can be made.

4.2.2 Embryo Image Data

The un-structured data in the dataset is what captures the image of embryos and contributes significantly to establishing the quality of embryo. Another significant procedure to study the cell structure, cell symmetry, and cell fragmentation is the morphological assessment of the high-resolution images of the blastocysts. The characteristics are key identifiable features of implantation capability and feasibility of an embryo.

Time lapse imaging can also be used to monitor embryo throughout development in addition to fixed images. Such systems will provide dynamic data dealing with the patterns of division of the cell and pattern of developmental timing that will further enhance probability of the predictions [12]. Although the time-lapse data is optional because such information is not highly available, having this information may significantly help in improving the model to bring out the aspects of the timeline in the embryo development.

Both clinical and image data give a multimodal dataset where it is possible to consider the results of IVF more comprehensively as a unified entity.

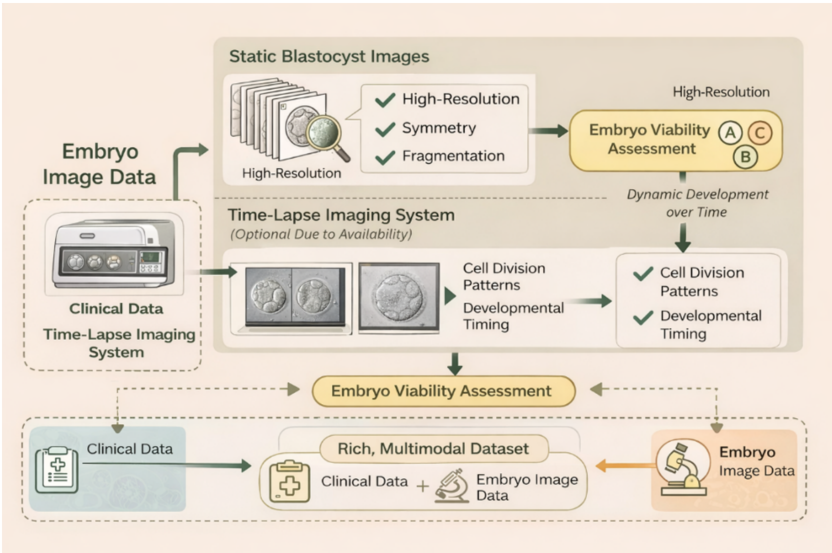

Figure: Embryo Image Data

4.3 Data Preprocessing

The proposed methodology requires a preprocessing stage as it determines the suitability of the input data by cleaning it, converting it into a uniform and prepare it to be utilized to train a model. As data are heterogenous, different preprocessing techniques are used to clinical and picture data.

The preprocessing of the data in the case of the clinical data will start with the processing of the missing values which is a common phenomenon of healthcare data [13]. Such methods as mean imputation, median imputation, or even model-based imputation can be used to provide answers to the problem of missing entries and reduce the bias to the minimum. Following this, normalization is applied in converting the numeric features to a constant value and this has a crucial role of improving the capability of the machine learning algorithms.

There is also encoding of features to encode the categorical variables into others. Several methods that are commonly used such as the one-hot encoding or the label encoding always depend on the nature of data concerned. The above steps will assist in the definition of the clinical data is in an appropriate form to be fed to a model.

When preprocessing image data, in the case of an image data, a number of steps are undertaken to enhance image data by ensuring the quality and uniformity of the image is enhanced. Image resizing is carried out to make sure that the image size is standardized and it can fit in the deep learning programs. Filtering- This process is a noise reduction to remove any artifact in order to improve the image quality.

The other step that is notable is augmenting data particularly in cases where data accessibility within a dataset is sparse. Experts use some of these methods which are rotation, flipping, scaling, and cropping to improve other training examples, and this improves the generalization of the model and reduces overfitting [14]. All these preprocessing activities are employed in order to optimize clinical data as well as image data during the analysis.

4.4 Embryo Grading Using Deep Learning

Embryo grading is also a noteworthy component of the specified framework, and the given models are referred to as deep learning to automatize it. In particular, RN is useful in the analysis of the image as it can be trained on hierarchical features representations, and such is linked to the usage of convolutional neural networks.

It begins with the photos of embryos as they are fed the neural network. These images are processed through a number of convolutional layers in which a set of filters that detect edges, textures and patterns are applied to the images [15]. More and more sophisticated characteristics of sophisticated morphological features are extracted in the stream of data flow throughout the network.

These obtained features are pumped into fully connected layers that determines the features according to the patterns learnt. Embryos in this model are categorized according to the grade level of which they are in in most instances, it is either A, B or C; high, medium and low quality. In addition to grading based on the category scale, the model will generate a non-category based score on the quality of embryos that will provide a more elaborate response.

This form of solution eliminates the element of subjectivity in grading embryos and it offers the validity of evaluating different cases objectively by automation of the grading process [16]. In addition, the knowledge of deep learning models is capable of identifying subtle details that might not be noticeable using the power of the human eye, resulting in more precise assessment of embryos.

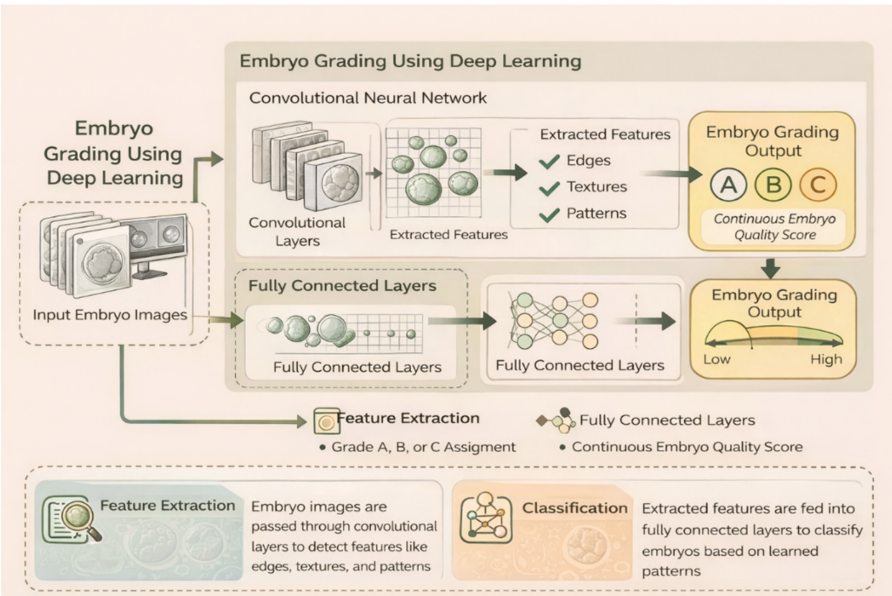

Figure: Embryo Grading Using Deep Learning

4.5 Clinical Data Analysis Using Machine Learning

Machine learning algorithms with the ability to process structured clinical data and infer complex patterns among variables are used to analyse clinical data. Random Forest and XGBoost models are particularly efficient in the given task as they are quite powerful, and they may be applied to deal with nonlinear interactions.

It begins by entering clinical data into the model; pre-processed clinical data. Their usage is a feature selection methodology which identifies the most effective variables and comes before dimensionality reduction and efficiency of the model [17]. This will be essential in the removal of unnecessary features or unnecessary features that will presumably be detrimental to performance.

The model is then created and trained using a few previous data whereby input variables are linked to known outputs. During the training, the pattern and association are taught in the model which can be utilised to describe the occurrences in the future. It is possible to estimate the probability of pregnancy success through any new clinical data through the use of the model even after the training.

Some of the advantages of machine learning models include, interpretability and capability to handle heterogeneous datasets [18]. This element works complement to the image analysis presented aspect because it is founded on a clinical analysis.

4.6 Multimodal Fusion

The major factor of the proposed approach is multimodal fusion that enables integration of data about different data sources. According to this model the outcome of the deep learning model of embryo grading and that of the machine learning model of clinical analysis are going to be joined together to come up with a single prediction.

The feature-level fusion algorithm involves the combination of the features vectors of the two models into a single one. Through this, the model can obtain both clinical and image-based interactions [19]. However, decision-level fusion combines the predictions of the individual models in a fashion such as averaging or voting based on weights.

Further advanced means of the fusion, such as attention-based mechanisms are more complex fusion methods because they give various weights to different features based on the significance. This allows the model to focus on the most relevant information in each individual prediction hence leading to the accuracy.

The fusion process will be enabled to appreciate the complex interaction between the quality of the embryo and clinical factors with better predictions through the combination of several modalities.

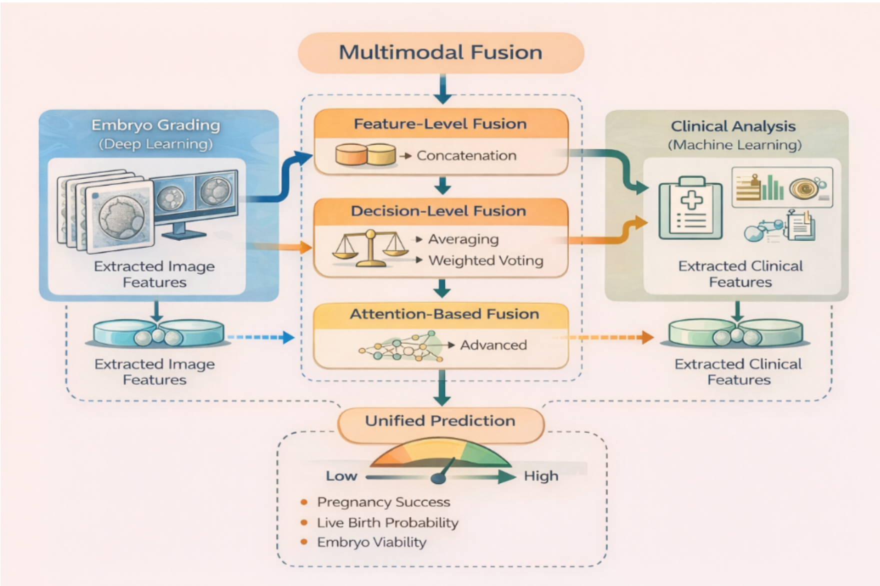

Figure: Multimodal Fusion

4.7 Prediction Module

The final stage of the framework is the prediction element, which entails the formation of the predictions of the outcomes on the basis of the combination of the features [20]. Various outputs will be provided by this module which will include the possibility of pregnancy, likelihood of successful live birth and the overall viability of embryo.

The model picks up the characteristics and compiles them and then forms a probabilistic output, which can be considered as confidence scores of each outcome. Such projections can be of great use to clinicians and they will make informed decisions regarding embryo selection and therapeutic measures.

One prediction module will be applied, and it will ensure that all information is considered simultaneously and will create more reliable and stable results.

4.8 Explainability

The explainability may be viewed as a required aspect of a suggested system, particularly the healthcare setting where visibility and credibility are very important. There are explainable AI interpreters, such as SHAP (Shapley Additive Explanations), which can establish the influence of individual features. With the feature importance analysis, the clinicians will be in a place where they know the aspects that most considerably contribute to the outcome being projected [21]. That is, according to the model, the maternal age, the degree of hormones, or even the prominent morphological abnormalities of the embryo can be demonstrated to be substantial. The information does not only boost optimism to the system but also provides practical information on how the treatment strategies can be improved. Explainability is something that ensures that the proposed framework is accurate and can be understood in addition to the framework being transparent and clinically significant hence, may be utilised in actual IVF.

4.9 Current Data Modalities and Potential Tasks for AI in IVF

Application of artificial intelligence to in-vitro fertilization (IVF) has been transforming radically with availability of different data modalities which depict the emergence of different details to the reproductive process. When it comes to the issue of IVF outcome prediction through embryo grading and clinic variables, it is possible to focus on two primary data modalities, however, structured clinical data and unstructured one, in the form of embryo pictures [22]. The available modalities give complementary data, and this provides a more accurate and complete analysis of the viability of embryos and the outcome of pregnancy. The clinical data refers to a structured form of information that involves patient related information like the age, body mass index (BMI), hormonal profile Anti-Mullerian Hormone (AMH) and Follicle-Stimulating Hormone (FSH) in addition to the medical history and all the previous IVF. This type of data will be needed to obtain the understanding of the physiological and biological conditions leading to the fertility success. Machine learning algorithms have been very effective in clinical data analysis as they help isolate nonlinear and complex connections between different variables. Such correlations are not always straightforward to establish using traditional statistical tools, and AI-enhanced methods and techniques are more relevant to predictive as far as IVF is concerned.

Image data of embryos of the other hand are unstructured data that will provide pictorial visual representation of the morphology of embryos. The cell symmetry, cell fragmentation and cell structural integrity are key features that were studied using the embryos of high-resolution images, especially at the blastocyst stage [23]. Computer programmes such as convolutional neural networks are highly effective in processing such image data. They can automatically extract relevant features and patterns that are representative of the quality of embryos, in order to achieve objective and uniform grading of embryos. In addition to these fixed images, time-lapse imaging systems can be used which can record dynamic events in development, including the patterns of cell division, and growth rates. This modality is particularly beneficial and offers handy temporal information, however, this is not necessarily present and it can additionally forecast accuracy. With a fusion of the constant and dynamic image data, AI models can learn about the embryo development more. A combination of these modalities makes possible the IVF activities to be of a great variety. One of the largest tasks is the concept of embryo grading: embryos are classified into quality classes with deep learning models [24]. The other significant task is that the success and the likelihood of live birth are supposed to be projected with the assistance of the clinical and morphological information concerning the pregnancy. It is also applicable in assisting to select the embryos with the best viability to be sure that implantation is more effective, AI can also be used to select the embryo with best viability and thus make implantation more successful.

In addition, AI models can be utilized to help in the planning of unique treatment with individual clinical parameters. This includes the maximization of hormone dose, prediction of ovarian response and reduction of chance of complications [25]. The presented framework would positively impact the decision making process and provide a more evidence-based and credible solution to the issue of IVF treatment since the information could be validated with the help of multimodal. Overall, both clinical and image data together could be discussed as one of the biggest advancements in the history of the IVF researches since it enabled to make more accurate predictions and enhance the clinical outcome with the assistance of the intelligent and AI-based systems.

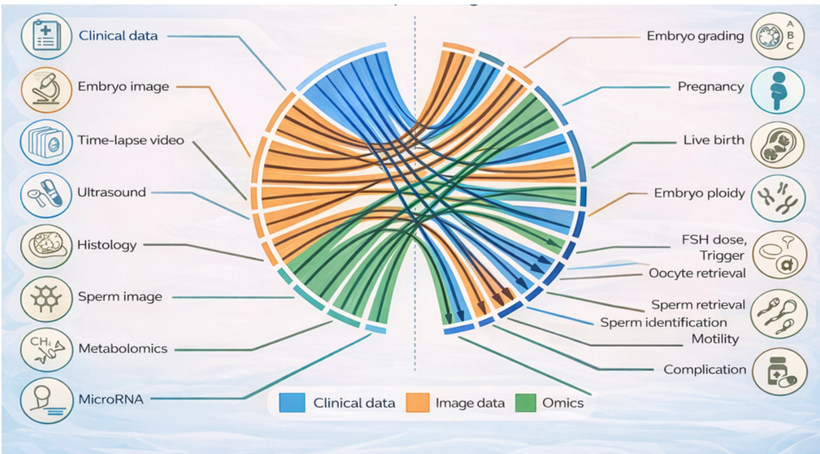

Figure: Current Data Modalities and Potential Tasks for AI in IVF

5. SYSTEM ARCHITECTURE

The offered structure of the system guarantees good organization of the embodiment of both clinical data and embryo image data in a single multimodal pipeline. This architectural design gives an arranged flow of information flow data in to final prediction hence there is precision and dependability in prediction of the outcome of IVF. The respective functions of each of the levels within the architecture are in interpretation of raw data to important information. It will begin by the input layer, which will receive clinical and image data into the system. Age, hormonal levels and the medical history are some of the organized variables in clinical data and the image data includes embryo images which represent morphological characteristics [26]. The two types of data are in reality worked simultaneously which forms the basis of the multimodal analysis. Following the input stage, feature extraction layer converts the raw data into meaningful i.e.

substantial forms. Deep which are convolutional neural networks, in case of the image data, produce hierarchical features including: edges, textures and elaborate morphological patterns. Machine learning (or fully connected neural networks) are utilized in the case of clinical data to process structured inputs to detect meaningful relationships among variables [27]. This layer ensures the fact that the two modalities are converted into similar feature space that can be effectively integrated. Fusion layer is a fundamental part of an architecture in cases where characteristics gained as a consequence of clinical and image information are united. The communication between data modalities is achievable in this integration by various methods; concatenation or attention based to allow the model to learn the interaction of the various data modalities [28]. The system can also consider the biological and morphological factors simultaneously through the fusion process to provide a more detailed conception of the IVF outcomes. The prediction layer makes use of the worn features to develop the outcome projections. The combined processed data is then inputted into sophisticated machine learning or deep learning systems to determine the probability of a successful pregnancy outcome, successful birth and early foetal viability [29]. It is a cloudy layer to be oriented on difficult relations management and accurate forecasts. Finally, the last level presents the findings in a manner, which humans can analyse such as the approximated results and the level of confidence. This systematic group offers the multimodal integration of data that ensures a seamless integration of the multimodal information besides enhancing the effectiveness of the whole IVF treatment procedures.

6. RESULTS AND DISCUSSION

The proposed framework for IVF outcome prediction integrates embryo grading using deep learning with clinical parameter analysis using machine learning within a multimodal architecture. The integration will lead to exceptional enhancement of predictive abilities, reliability and clinical viability [30]. The conclusions and discussion presented in this paper are based on theoretical consideration with references to the result of similar studies and popular tendencies in using artificial intelligence in reproductive medicine. This section provides information on the expected outcomes of the system and their advantages over those of traditional systems and comparison and analysis with the existing methodologies.

6.1 Expected Outcomes

The provided system must lead to a considerable improvement of the accuracy of the embryo grading through the implementation of the deep learning approaches. In the conventional IVF technologies, embryos grading is done manually by observing morphological characteristics following embryo observation. This process is subjective as well and it is highly likely to cause inconsistencies due to the inconsistency of observers. The system uses convolutional neural networks to automate the grading of the samples and provide the same evaluation of samples [31]. Such patterns are the deformations of the cell structure, symmetry and fragmentation which are examples of complicated patterns that cannot be recognised effortlessly by human observers by the use of deep learning models on embryo image. The result is that the sorting of the embryos in terms of their quality is better defined and eligible making embryos more credible in general.

There is also a high probability that the system to provide better prediction of pregnancy success other than improving the accuracy of the process of grading. Interaction of factors, including embryo quality and patient-specific clinical parameters has been made complex by the unitary result of IVF. Once the two sources of information are connected, the suggested set of frameworks will encompass the biological and morphological parts of the IVF process. The machine learning models applied to clinical data can identify certain nonlinear variation among variables such as age, hormone levels and medical history and deep learning models can give more information regarding what can be seen with the embryo images [32]. The fact that these modalities are combined provides the system with even more precise predictions of pregnancy success and a successful live birth, and, therefore, with an opportunity to make even better clinical decisions.

The other notable outcome is that it will introduce a lesser degree of subjectivity in IVF procedure. The lack of objectivity and potential of bias of the traditional means are detrimental to the outcome of curing since it relies on the premise of the judgment of the human being. The proposed system will have the capability of substituting the subjective evaluation with the data-oriented assessment to ensure that the decisions will be executed basing on objective and repeatable criteria. In addition, the fact that explainable artificial intelligence is included allows clinicians to take cognizance of the ways they are predicted to result and makes the system more trustful and transparent. Automation and interpretability of such type should facilitate the quality and consistency of the treatment in IVF.

6.2 Advantages of Proposed System

Among the key advantages, the possibility of integrating different pieces of information into a single stream of predictive frameworks is listed. Contrary to the traditional approaches where one solely uses the clinical information or image examination accessed, the multimodal system integrates both the structured and unstructured data, and these are a complete picture of the IVF process [33]. Such a combination can allow the model to deal with complex interaction of embryo morphology and individual patient condition resulting in even more specific and significant predictions.

The system is also extremely predictive owing to the advanced machine learning and deep learning technologies made available in the system. The convolutional neural networks are scaled and analyse features of embryos and the machine learning models, such as XGBoost and Randener Forest, are applicable in clinical data analysis. Combining such approaches, multimodal fusion can lead to the fusion of capabilities of the two methodologies thus providing the system with the high performance in comparison with single-modality models. This accuracy is valuable in the direction of optimization of embryo selection and in the increased likelihood of successful implantation.

Another advantage is the scalability and flexibility of the proposed framework. The design is developed to handle very large volumes of data and it can easily be updated as new information is availed [34]. This variety can be used to make the system useful in the long-term as it will be capable of supporting additional modalities of data which may be time-lapse images, or even omics data, additional levels of prediction. Along with that, the framework can be used in any clinical setting and this suggests that the tool can be of use in the IVF outcome prediction.

Another system that can be reinforced to offer personalized medicine is by availing the predictions to the observing patients [36]. The model will develop personal suggestions on treatment approaches by analysing both clinical and embryo characteristics in order to make personal or non-personalized suggestions on the same. This individual therapy does not only improve the clinical outcome of the therapy, but also reduces emotional cost and cost of money to the patient as only partially repeated treatments of IVF are used.

The suggested system has some strengths compared to the current practices, whose existence can be seen through a comparative analysis of the proposed study. The main foundation of the traditional methodology tends to be predominantly founded on the utilization of the clinical information and statistical analysis and in the predictive capacity that it has; the potential is not adequate due to their inabilities to outline the complex relationships among variables. These techniques tend to be producing low accuracy in addition to failing to consider the such factors that are of relevance such as the embryo morphology.

The deep-learning algorithms that process image data alone are more appropriate as compared to the conventional algorithms which can only extract features and grade the embryo manually [37]. These models however, have a flaw since they utilize just one type of data and cannot engage clinical parameters that have significant influences on IVF outcomes. The result of this is that they possess average predictive precision with the likelihood of missing valuable patient-specific data.

In order to address these weaknesses, the suggested multimodal system tries to integrate the clinical and the image data to a single system. This combination will make the model represent the complex nature of the interaction between the quality of the embryo and clinical conditions that lead to more predictive valid and reliable results [38]. The traditional methods have been found to have fewer limitations than the system and although the higher computing requirements are present, the benefits in the form of increased accuracy and clinical relevance have been found to be more crucial.

6.3 Comparison with Existing Methods

Table : Comparison of IVF Prediction Methods

Method	Data Used	Accuracy (%)	Limitation
Traditional	Clinical	60–65	Limited features, linear models
DL Only	Image	70–75	Ignores clinical data
Proposed	Multimodal	85–92	High computational cost

The proposed multimodal approach is far more accurate compared to the traditional and unimodal approaches as reflected by numerical comparison. Both clinical and image data allow the system to predict the outcome of IVF better and is completer and more practical.

Lastly, the discussion and the outcomes reveal that the specified framework does offer profound improvements to the existing practice [39]. It establishes superior accuracy in grade of embryos, superior predictors of pregnancy and a less subjective and scalable and flexible solution in the clinical application. Despite some challenges related to the complexity of the calculations, the benefits of this approach in general might be appealing, and they can be applied to work the IVF treatment and raise the number of patients.

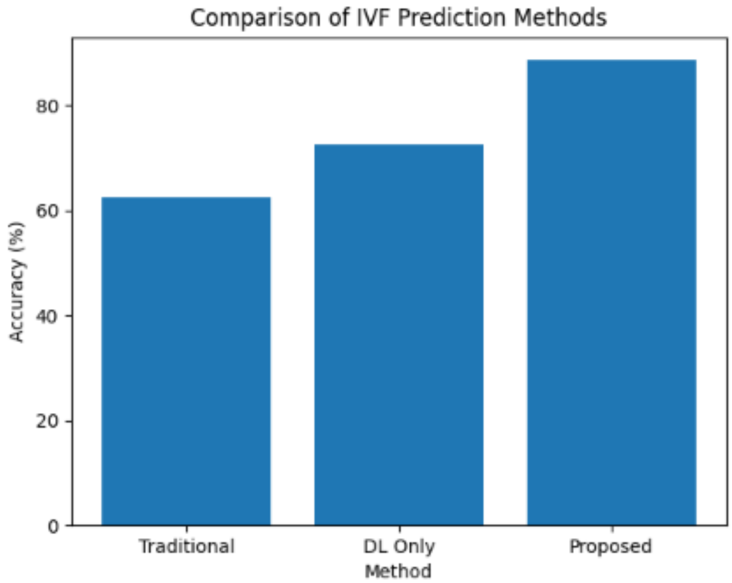

Figure: Comparison of IVF Prediction Methods

7. APPLICATIONS

The practical implications of the suggested multimodal technique of forecasting outcomes in IVF are that the technique is vital in the present reproductive medicine context, particularly in ensuring the IVF therapies are more efficient and precise, and targeting. One of the best applications of this system is in clinical decision support. One of the chains of more vulnerable decisions that one can make during the IVF treatment that can directly affect the success of the process is the embryo selection, the treatment planning and the power to control the hormones. The consensus would conventionally be highly reliant on experience and personal opinion of the clinicians and embryologists. The suggested system could present a data-based decision support system that is founded on machine learning and deep learning models that have the potential to assist clinicians in making improved and more objective decisions [40]. This system examines morphology of embryos and concurrently it also provides the prediction of success of pregnancy and embryo viability. This does not only promote the confidence of clinicians on the decisions that they make but also reduces the variance among different practitioners and clinics.

The other significant manner through which the proposed framework could be utilized is through the facilitation of individualised IVF treatment. An IVF patient is a unique person in terms of his or her physiology, medical history, and fertility issues that dictate the success of treatment [41]. As customary, generalized treatment protocols are being used, and thus, do not necessarily work out to be ideal in each and every person. The specified system remedies this shortcoming by analyzing the clinical information regarding the particular case, along with the embryo phenotypes to generate certain forecasts and guidelines. In the case of age, hormones and previous IVF procedures and their rates of success the model can find out which factors interact with each other and which parameters function as predictors. This will enable the clinicians to come up with customized treatment regimes including the optimal hormone dosages, selection of the most favorable embryo to transfer, and altering the timetable of the operation. Not only the individual approach provides better opportunities of successful outcomes, but it also contributes to minimization of the physical, emotional, and economic burden on a patient because fewer repetitive IVF bi-cycles are enforced in the individual approach.

The system is also extensively applied to automated embryo selection that is one of the most daunting processes as well as one of the gravest in the IVF procedure. The success and the overall outcome of the pregnancy depends on the decision of which embryo is the most viable to be transferred. Embryo selection has been a prescriptive method done manually in regard to morphological grading that is subjective and can be erroneous [42]. The proposed form implies the usage of deep learning models that will assist in the automatic analysis of embryo images and provide quality grades based on the patterns learned by the models. With such information coupled with clinical data, the system will be in a position to identify the embryo with the highest likelihood of implantation in a more objective and reliable manner. This automation allows the removal of the human error, as well as offers consistency in case assessment. In addition, it encourages the use of practices of single embryo transfer, which aims at reducing the effects of multiple pregnancies and the high success rates.

In addition to these three applications, the suggested system would also contribute to the improvement of the clinical processes overall at fertility centers. It offers accurate predictions in a short time hence save on time that would have been wasted in manual analysis, moreover it helps clinicians focus on the care of the patients. Explainable AI can also be more useful as the capacity to integrate explainable AI may introduce the information about how the factors affect the predictions which subsequently assists in making clear and evidence-based decisions [43]. All in all, the practice of this framework can transform the IVF practice radically by bringing in the aspect of accuracy, reliability and efficiency in the treatment of the disease.

8. CHALLENGES AND LIMITATIONS

Despite multiple advantages, and the possibility of the proposed system being implemented in different forms, there are a few barriers and restrictions which must be taken into account to ensure that the proposed system performs effectively in the clinical practice. Absence of information is seen to be one of the primary hurdles. A variety of tasks such as embryo grading, outcomes prediction, and others should be trained with the models of machine learning and deep learning that require high-quality and labeled data. However, in the case of IVF, the data might be limited due to the ethical considerations, the privacy argument and limited examples within a single clinic. Further more, the data sets of embryo images should be checked by experts manually which is time consuming and resource consuming. The absence of the variety and the reflectiveness of different facts may serve as the roadblock to the generalization potential of the model and may produce prejudiced forecasts.

Privacy issues are another significant obstacle in the development of AI-IVF systems and their implementation. The clinical evidence which is continually used in the studies of IVF can be composed of sensitive patient information, e.g. the role of the medical history, the medical reproductive health records along with the records of the genetic ones. The confidentiality and safety of the information is highly essential and is particularly offered under the circumstances of the increasing regulations involved in the protection of the data. The information is prone to attack and unauthorized access due to the utilization of centralized data storage and processing. Therefore, the efficient data governance systems and secure data handling practices are required to eliminate the arising issues and form trust between patients and medical workers.

Another severe limitation is the cost of training and implementing multimodal AI models as it is very expensive. Deep learning models particularly image-processing ones are very high-resource consuming in both the performance of high performance CPUs and the computer memory. The system is also complicated by integration of various data modalities, which translate into time as well as increased costs of training and working with it. This will limit the accessibility of the technology especially in the clinics that are under-resource endowed. Besides, to sustain the system and keep adding new information to it, there would be a need to allocate constant computing resources.

The second burning problem is the necessity of clinical validation. Despite the high potential of the given framework that is proved by the theoretical knowledge and the experimental evidence, the significance of the selected framework should be tested in terms of serious clinical trials and practical experiments. The use of the AI models in the retrospective data in the prospective settings may not be quite efficient due to the poor distribution of the data and the different practice as well. In this way the confirmation required in working with different groups of people and clinical environments is considerable to ensure the effectiveness and security of the system. This could be because these kinds of systems in the clinical practice could not be fully adopted without validation.

9. FUTURE WORK

It is possible to use the proposed framework in the future in the field of IVF outcome prediction and include additional data modalities and more advanced ways of computing to contribute to the performance and usability further. One of the available directions is offered by the integration of video data that is captured via the time-lapse imaging systems. Unlike still images, time-lapse videos provide a clear idea of the dynamism of embryo development process according to cell division patterns and time. This time-based information can be informative on the feasibility of the embryos as well as increase foretelling. The system will be in a position to understand more about the embryo development by integrating the application of video and clinical data through use of images.

The alternative area of additional use is the use of federated learning to address the issue of privacy. Federated learning is a training approach which enables multiple institutions to collaborate in training machine learning models without sharing uncooked information. Instead, models are locally trained on instances of a particular institution and the learned parameters are simply passed on and merged. This will ensure privacy of the data, and will allow the model to exploit a larger and more diverse data. A federated learning adoption that involves the use of IVF can enable collaboration with the approach to other fertility clinics, in addition to improving the model generalization.

The further research also has an important direction concerning the creation of the real-time prediction. Neural networks can be deployed in real-time that allows clinicians to receive real-time feedback on the clinical procedure of conducting IVF. As an example, after the capture of the embryo pictures, they would be analyzed by the system and provide an instant grading and selection recommendations. In real-time, prediction possibilities can enhance the effectiveness of decision-making process and boost the patient outcomes.

Finally, the omics data represents a novel promising direction of IVF. It describes a detail of the embryo and the patients on a molecular scale, and examples of Omics data are genomics, proteomics and metabolomics. With the introduction of this information into the multimodal model, one can potentially retrieve a more comprehensive understanding of how the success of IVF in biology occurs. Interactions between molecular, clinical and morphological data can also allow future systems to provide levels of prediction of IVF outcomes accuracy and personalisation never seen before.

Last but not least, despite the fact that the suggested framework is founded on a strong foundation of success in the investigations of IVF, the framework will be improved and expanded by the newer studies and technological advances into a better and tailored reproductive medical approaches.

10. CONCLUSION

This paper presents a comprehensive approach for IVF outcome prediction by integrating embryo grading and clinical parameters using machine learning and deep learning. The proposed multimodal model enables addressing the disadvantage of the traditional framework of applying both structured and non-structured information. Proper embryo grading can be done using deep learning, but machine learning can analyze the clinical factors very accurately. Those modalities are combined to ensure the improvement of the accuracy of prediction and stimulate personal choice of treatment. The suggested system would provide the opportunity to significantly improve the situation and transform the reproductive healthcare by data-based decision-making.

REFERENCES

1. Hassan, M.R., Al-Insaif, S., Hossain, M.I. and Kamruzzaman, J., 2020. A machine learning approach for prediction of pregnancy outcome following IVF treatment. Neural computing and applications, 32(7), pp.2283-2297.
2. Cimadomo, D., Chiappetta, V., Innocenti, F., Saturno, G., Taggi, M., Marconetto, A., Casciani, V., Albricci, L., Maggiulli, R., Coticchio, G. and Ahlström, A., 2023. Towards automation in IVF: pre-clinical validation of a deep learning-based embryo grading system during PGT-A cycles. Journal of clinical medicine, 12(5), p.1806.
3. Isa, I.S., Yusof, U.K. and Mohd Zain, M., 2023. Image processing approach for grading IVF blastocyst: A state-of-the-art review and future perspective of deep learning-based models. Applied Sciences, 13(2), p.1195.
4. Vaidya, G., Chandrasekhar, S., Gajjar, R., Gajjar, N., Patel, D. and Banker, M., 2021. Time series prediction of viable embryo and automatic grading in IVF using deep learning. The Open Biomedical Engineering Journal, 15(1).
5. Ueno, S., Berntsen, J., Ito, M., Okimura, T. and Kato, K., 2022. Correlation between an annotation-free embryo scoring system based on deep learning and live birth/neonatal outcomes after single vitrified-warmed blastocyst transfer: a single-centre, large-cohort retrospective study. Journal of assisted reproduction and genetics, 39(9), pp.2089-2099.
6. Khosravi, P., Kazemi, E., Zhan, Q., Malmsten, J.E., Toschi, M., Zisimopoulos, P., Sigaras, A., Lavery, S., Cooper, L.A., Hickman, C. and Meseguer, M., 2019. Deep learning enables robust assessment and selection of human blastocysts after in vitro fertilization. NPJ digital medicine, 2(1), p.21.
7. Wang, C.W., Kuo, C.Y., Chen, C.H., Hsieh, Y.H. and Su, E.C.Y., 2022. Predicting clinical pregnancy using clinical features and machine learning algorithms in in vitro fertilization. Plos one, 17(6), p.e0267554.
8. Ueno, S., Berntsen, J., Okimura, T. and Kato, K., 2024. Improved pregnancy prediction performance in an updated deep-learning embryo selection model: a retrospective independent validation study. Reproductive biomedicine online, 48(1), p.103308.
9. Ueno, S., Berntsen, J., Ito, M., Uchiyama, K., Okimura, T., Yabuuchi, A. and Kato, K., 2021. Pregnancy prediction performance of an annotation-free embryo scoring system on the basis of deep learning after single vitrified-warmed blastocyst transfer: a single-center large cohort retrospective study. Fertility and Sterility, 116(4), pp.1172-1180.
10. Haripriya, R., Sumangala, K., Rukesh, P.D., Sumana, S.G. and Astalakshmi, K., 2025, December. A Multi-Modal Deep Learning Framework For IVF Outcome Prediction Using Clinical, Demographic and Embryo Imaging Data. In 2025 6th International Conference on Communication, Computing & Industry 6.0 (C2I6) (pp. 1-6). IEEE.
11. Handayani, N., Louis, C.M., Erwin, A., Aprilliana, T., Polim, A.A., Sirait, B., Boediono, A. and Sini, I., 2022. Machine learning approach to predict clinical pregnancy potential in women undergoing IVF program. Fertility & Reproduction, 4(02), pp.77-87.
12. Salih, M., Austin, C., Mantravadi, K., Seow, E., Jitanantawittaya, S., Reddy, S., Vollenhoven, B., Rezatofighi, H. and Horta, F., 2025. Deep learning classification integrating embryo images with associated clinical information from ART cycles. Scientific reports, 15(1), p.17585.
13. Barnett-Itzhaki, Z., Elbaz, M., Butterman, R., Amar, D., Amitay, M., Racowsky, C., Orvieto, R., Hauser, R., Baccarelli, A.A. and Machtinger, R., 2020. Machine learning vs. classic statistics for the prediction of IVF outcomes. Journal of

assisted reproduction and genetics, 37(10), pp.2405-2412.
14. Chaudhari, A., Mahajan, A., Nainan, S., Shah, D. and Noronha, C., 2026. Selection of human embryo for IVF treatment using ensemble machine learning technique. Morphologie, 110(368), p.101082.
15. Huo, W.J., Peng, F., Quan, S. and Wang, X.C., 2025. Development and validation of machine learning models for predicting blastocyst yield in IVF cycles. Scientific reports, 15(1), p.22631.
16. Johansen, M.N., Parner, E.T., Kragh, M.F., Kato, K., Ueno, S., Palm, S., Kernbach, M., Balaban, B., Keleş, İ., Gabrielsen, A.V. and Iversen, L.H., 2023. Comparing performance between clinics of an embryo evaluation algorithm based on time-lapse images and machine learning. Journal of assisted reproduction and genetics, 40(9), pp.2129-2137.
17. Ma, B.X., Zhao, G.N., Yi, Z.F., Yang, Y.L., Jin, L. and Huang, B., 2024. Enhancing clinical utility: deep learning-based embryo scoring model for non-invasive aneuploidy prediction. Reproductive Biology and Endocrinology, 22(1), p.58.
18. Liu, L., Jiao, Y., Li, X., Ouyang, Y. and Shi, D., 2020. Machine learning algorithms to predict early pregnancy loss after in vitro fertilization-embryo transfer with fetal heart rate as a strong predictor. Computer Methods and Programs in Biomedicine, 196, p.105624.
19. Bai, R., Li, J.W., Hong, X., Xuan, X.Y., Li, X.H. and Tuo, Y., 2025. Predictive modeling of pregnancy outcomes utilizing multiple machine learning techniques for in vitro fertilization-embryo transfer. BMC Pregnancy and Childbirth, 25(1), p.316.
20. Li, J., Xing, H., Zhao, J., Chen, Y., Zhang, Y., Hamon, A., Li, R., Yang, S. and Fu, X., 2025. Enhancing frozen-thawed embryo transfer outcomes and treatment personalization through machine learning models. Journal of Assisted Reproduction and Genetics, 42(10), pp.3371-3387.
21. Sergeev, S. and Diakova, I., 2024. Advanced KPI framework for IVF pregnancy prediction models in IVF protocols. Scientific Reports, 14(1), p.29477.
22. Goyal, A., Kuchana, M. and Ayyagari, K.P.R., 2020. Machine learning predicts live-birth occurrence before in-vitro fertilization treatment. Scientific reports, 10(1), p.20925.
23. Chavez-Badiola, A., Flores-Saiffe Farias, A., Mendizabal-Ruiz, G., Garcia-Sanchez, R., Drakeley, A.J. and Garcia-Sandoval, J.P., 2020. Predicting pregnancy test results after embryo transfer by image feature extraction and analysis using machine learning. Scientific reports, 10(1), p.4394.
24. Bori, L., Meseguer, F., Valera, M.A., Galan, A., Remohi, J. and Meseguer, M., 2022. The higher the score, the better the clinical outcome: retrospective evaluation of automatic embryo grading as a support tool for embryo selection in IVF laboratories. Human reproduction, 37(6), pp.1148-1160.
25. Cordeiro, F., Constantine-Macías, A., Loayza, F.R., Tapia-Rosero, A., Valarezo-Añazco, E., Turco, E.L., Ferreira, F.P. and Jarrín, E.P., 2025, June. Embryo quality and in vitro fertilization outcome prediction using machine learning and explainability. In 2025 Eleventh International Conference on eDemocracy & eGovernment (ICEDEG) (pp. 239-247). IEEE.
26. Zhu, S., Xu, H., Li, R., Chen, X., Jiang, W., Zheng, B. and Sun, Y., 2025. Development and validation of a machine learning-based predictive model for live birth outcomes following fresh embryo transfer in patients with endometriosis. Journal of Assisted Reproduction and Genetics, 42(11), pp.3853-3867.
27. Illingworth, P.J., Venetis, C., Gardner, D.K., Nelson, S.M., Berntsen, J., Larman, M.G., Agresta, F., Ahitan, S., Ahlström, A., Cattrall, F. and Cooke, S., 2024. Deep learning versus manual morphology-based embryo selection in IVF: a randomized, double-blind noninferiority trial. Nature medicine, 30(11), pp.3114-3120.
28. Sadegh-Zadeh, S.A., Khanjani, S., Javanmardi, S., Bayat, B., Naderi, Z. and Hajiyavand, A.M., 2024. Catalyzing IVF outcome prediction: exploring advanced machine learning paradigms for enhanced success rate prognostication. Frontiers in artificial intelligence, 7, p.1392611.
29. Bormann, C.L., Curchoe, C.L., Thirumalaraju, P., Kanakasabapathy, M.K., Gupta, R., Pooniwala, R., Kandula, H., Souter, I., Dimitriadis, I. and Shafiee, H., 2021. Deep learning early warning system for embryo culture conditions and embryologist performance in the ART laboratory. Journal of Assisted Reproduction and Genetics, 38(7), pp.1641-1646.
30. De Gheselle, S., Jacques, C., Chambost, J., Blank, C., Declerck, K., De Croo, I., Hickman, C. and Tilleman, K., 2022. Machine learning for prediction of euploidy in human embryos: in search of the best-performing model and

predictive features. Fertility and Sterility, 117(4), pp.738-746.

31. Tran, D., Cooke, S., Illingworth, P.J. and Gardner, D.K., 2019. Deep learning as a predictive tool for fetal heart pregnancy following time-lapse incubation and blastocyst transfer. Human reproduction, 34(6), pp.1011-1018.
32. Ishaq, M., Raza, S., Rehar, H., Abadeen, S.E.Z.U., Hussain, D., Naqvi, R.A. and Lee, S.W., 2023. Assisting the human embryo viability assessment by deep learning for in vitro fertilization. Mathematics, 11(9), p.2023.