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Review Article

Beyond the limits of traditional diagnostics: the role of artificial intelligence in analyzing multimodal data for rapid virus detection

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Accurate and rapid diagnosis of viral infections is critical for effective public health responses. This article reviews traditional diagnostic methods including viral culture, PCR, and serological assays highlighting their limitations in scalability, speed, and adaptability to emerging outbreaks. In contrast, artificial intelligence offers transformative capabilities in analyzing medical images, genomic sequences, and multimodal data with unprecedented precision. The novel solutions presented in this article include convolutional neural networks in radiological imaging, transformer-based neural nets in genome biology, and integrated solutions to bringing clinical, molecular, and imaging data together. The arising methods such as single-molecule imaging through deep learning and artificial intelligence-based low-resource diagnostic methods are also discussed. A comparative analysis highlights the benefits of artificial intelligence compared to traditional methods in the areas of efficiency, scalability and clinical integration, and explore the issues of data quality, algorithmic bias and regulatory compliance. Finally, the article draws conclusions detailing its future directions, protein language models, federated learning and portable diagnostic platforms. At the end, the article recommends applications of hybrid diagnostic systems, combining conventional approaches with the artificial intelligence-driven technologies, and notes that interpretable algorithms and the cross-industry developmental efforts between artificial intelligence and health professionals, will be necessary to address emerging viral challenges.

Keywords: artificial intelligence; convolutional neural networks; deep learning; virus.

Introduction

Early detection and proper identification of viral infections is one of the pillars of successful public health response and clinical care. Conventional forms of diagnosis like viral culture, polymerase chain reaction (PCR) and serological testing are long term seasoned standards used in virology laboratories. These methods, although reliable, can be costly in terms of resources such as equipment, trained manpower, and time consuming, thus they can be cumbersome during an outbreak or in resource-poor environment.(1)

Artificial intelligence (AI) is a relatively recent technology that has found its application in the field of biomedical diagnostics, providing it with a new solution to the problem of the existing methods. Computationally intensive problems, such as medical image analytics, genomic sequencing, and clinical metadata, are capable of being analyzed with extreme speed and accuracy due to AI. Such technologies not only proved useful in finding the viral pathogens, but also in forecasting their infective behavior, their resistance and their epidemiology.(2)

This article aims to explore the latest advancements in AI-based viral diagnostics and compare them with traditional approaches across multiple dimensions, including accuracy, scalability, cost-effectiveness, and clinical applicability. It provides a thematic narrative overview of recent AI applications, integrating peer-reviewed findings and emerging technologies across imaging, genomics, and clinical deployment.

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Traditional methods for viral diagnosis: foundations and limitations

Traditional methods of diagnosis have taken years to become the fundamental aspects of clinical virology. The viral culture is one of the first choices which entails the isolation and growth of a live virus in cells. While it gives conclusive identification and subsequent phenotypic studies, it is too slow and may require days or weeks to complete and requires biosafety-level laboratory facilities. It is not very practical in urgent diagnostics or mass screening.[3]

PCR revolutionized the detection of viruses, by enabling the amplification of specific nucleic acids. Its high sensitivity and specificity, has made it a popular method to detect a broad range of viruses such as HIV, influenza and SARS-CoV-2. However, PCR has its limitations though. It is very much dependent on reagents, the availability of thermal cyclers, and competence of skilled technicians. Further falsely negative results could be obtained because of the sampling error or low viral loads at the beginning of infections.[4]

Antibodies or antigens can be detected using serological assays, e.g. enzyme-linked immunosorbent assays (ELISA). These tests are useful to diagnose retrospectively and to monitor epidemiologically, but less useful in the acute phase of infection concerning the formation of antibodies. Rapid lateral flow assays have been increasingly used during the COVID-19 pandemic as they are fast and easy to use. However, in most cases, they are not sensitive enough and can lead to false-negative results in asymptomatic or minimally-loaded cases.[5]

Although they have been shown to be useful, traditional methods have been found to be limited in these aspects: scalability, turnaround time, and suitability to new pathogens. Such restrictions highlight the necessity of complementary technology and solutions capable of streamlining the diagnostic workflows especially during an outbreak or in a decentralized environment.[1]

AI-based viral diagnosis: techniques and innovations

The field of viral diagnostics has undergone a paradigm shift with the emergence of data driven, scalable and highly dynamic tools powered by AI. In comparison to the traditional methods that are based on the biochemical reactions or are interpreted manually, AI systems can work with clinical, genomic, and imaging data and detect a viral infection with a great speed and accuracy. In outbreak cases, the systems are especially useful because a quick screening and early detection is a prime concern in outbreak control response.[5]

The area in which the application of AI in virology is most noticeable is the use of deep learning models, mainly convolutional neural networks (CNNs) to analyze medical images like chest X-rays and computed tomography (CT) scans. In the COVID-19 era, some of the studies have shown that AI models can perform the differentiation of viral pneumonia and alternative respiratory diseases with the diagnostic precision near to that of professional radiologists. These models trained on thousands of annotated images and could provide its outputs in a few seconds, which made them appropriate to be used on point-of-care devices.[2,6]

In addition to imaging, AI has also been utilized in analysis of genomic data. Sequencing can be used to detect viral mutations, categorize different strains and predict drug resistance through machine learning algorithms of viral RNA sequences. As another example, SARS-CoV-2 variants have been tracked with recurrent neural networks (RNNs) and transformer-based models in order to project their epidemiological impact. These have made it possible to monitor the virus in real time and also assist in the design of a vaccine as they identify regions that are conserved and not conserved within viral genomes.[7]

Single-particle imaging with the deep learning technique is another budding method of imaging. Researchers at the American Chemical Society (ACS) Nano have created a platform that can detect and characterize viruses within a few minutes through the analysis of their light, but unlike similar platforms, it can also identify an infected sample using AI algorithms. This method avoids requirements of amplification or labelling and can discriminate between several types of viruses during a single experiment.[8]

The impact of multimodal data integration has been significant, allowing for the combination of data from tests, laboratory results, imaging, and epidemiological

studies into a comprehensive overview of potential diagnoses. Based on this approach, end-to-end AI systems have been designed to classify respiratory diseases and directly detect COVID-19 at the point-of-care, providing a conceptual model of what future diagnostic systems should be like, i.e., autonomous and adaptive.[9]

Despite these advances, challenges remain. AI models require large, high-quality datasets for training, and their performance can degrade when applied to new populations or data sources. Moreover, interpretability and regulatory approval are ongoing concerns, especially in clinical settings where transparency is essential.[2]

AI-driven viral diagnosis pipeline

Viral diagnostics is being transformed through the use of IA to analyze ad hoc data much faster. The diagnostic pipeline starts with the recording of multimodal data or inputs such as X-rays (i.e. chest X-rays), RNA viral sequences, structured clinical documents among others. Such data are preprocessed through denoising, normalization, and feature encoding to ensure compatibility across modalities.[5]

Then, a more advanced deep neural network architecture will be used CNNs over images to extract features, transformer-based models to analyze sequences, and multimodal fusion networks to combine various data streams. Such models are trained to identify viral signatures, classify the type of infection and predict the severity of infection.[10]

A graphical overview of this workflow is provided in Figure 1, which depicts the AI-based workflow of the viral diagnosis pipeline that combines multimodal biomedical inputs, preprocessing steps, domain-specific deep learning models, and clinically actionable outputs.

The final stage involves generating diagnostic outputs, including virus identification, severity grading, and personalized treatment recommendations. This AI-driven approach enhances diagnostic precision, reduces time-to-result, and supports evidence-based clinical decision-making.

Clinical applications of AI in viral diagnostics

The application of AI in virus diagnostics has transitioned from theoretical concepts to real-world implementation. The use of AI-driven software in the hospital setting has become commonplace, thus making it easy to interpret the data contained in radiographic images, laboratory results, and symptoms associated with a patient. One notable example is the CNN, which has demonstrated high accuracy in determining whether

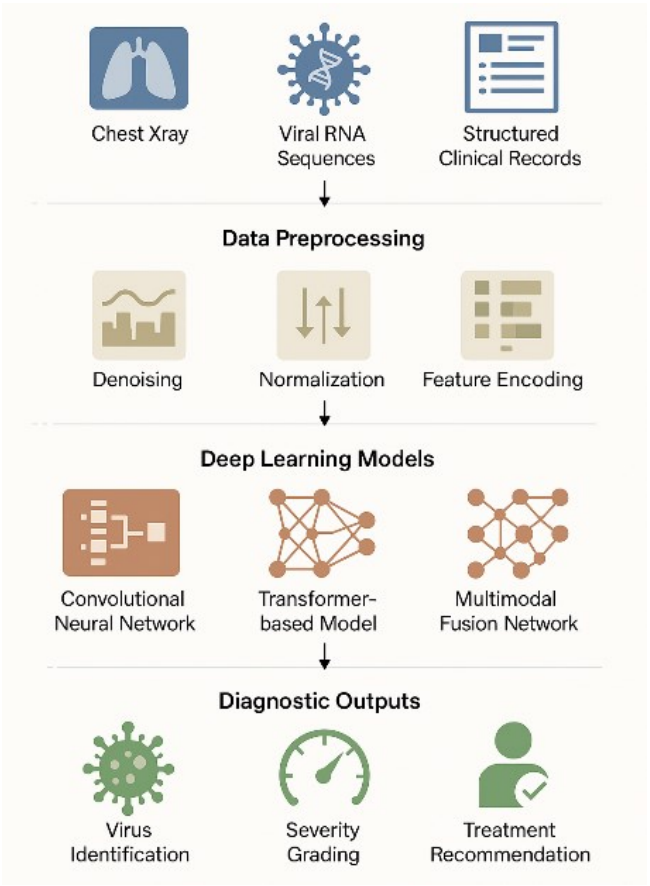


Fig. 1. Viral diagnosis pipeline based on artificial intelligence. The schematic diagram of a viral diagnostics pipeline based on artificial intelligence. In the multimodal biomedical input that the system combines, there are, among others, the following: the chest radiographs, the RNA sequences of the virus, and the structured clinical records of the patient that are processed by the system through the denoising, normalization, and feature encoding steps. Specialized deep learning architectures are used: for image recognition Convolutional Neural Network architecture, sequence recognition with Transformer based architecture and integrating learning with multimodal fusion networks. The pipeline products are the identification of virus, severity grading, and individualized treatment recommendations, which help to make personalized actions and support the quick and evidence-based clinical decision-making.

a patient has COVID-19 based on chest X-rays. In some cases, the accuracy of CNN has surpassed that of traditional radiologists, particularly in time-sensitive analyses.[11]

In addition, AI-based tools (e.g., BioMind and InferRead) have been successfully tested in multicenter studies that demonstrate their potential for diagnosing respiratory infections with real-time support and subsequent decrease in diagnosis turnaround times. By improving the precision of care and alleviating the burden on healthcare experts, these tools become imperative during outbreaks.[12]

Nevertheless, there are obstacles to clinical use that AI, although promising, has to cover, namely, interoperability, data privacy, and approval of use. To find solutions to these concerns becomes a necessity to integrate itself stable into routine diagnostics.[13]

AI in viral mutation analysis and development

AI plays a crucial role in tracking viral mutations and vaccine development. Machine learning algorithms have the ability to analyze large genomic data sets to determine mutation hotspots, extrapolate antigenic drift and model immune escape. Transformer-based model, e.g., ESMFold and ProtBERT, has been utilized in protein structure prediction and the evaluation of epitope stability under the mutational pressure.[14]

Such capacity is especially useful in monitoring viruses such as influenza and SARS-CoV-2, which mutate and change rapidly, requiring a prompt update of vaccination. Reverse vaccinology can also be enhanced by IA-based platforms to identify conserved regions among viral strains to speed up the development of multi-epitope vaccines. Immunoinformatics and structural biology, combined with AI, can maximize vaccines and shorten overall development. AI enables sensitive and adaptable discussions on vaccine pipelines to vaccine pipelines, lowering the development time and increasing the effectiveness.[15]

AI in resource-limited settings

AI provides a radical solution to diagnostic problems in resource-constrained environments. Applications of mobile-based AI, including smartphone-compatible biosensors and diagnostic solutions incorporated into a cloud system, provide an opportunity to conduct decentralized testing without requiring significantly advanced laboratory facilities.[3]

The tools are based on the use of lightweight models adapted to low-bandwidth environments so that symptoms, images or test results can be analyzed in real time. To give an example, AI-guided lateral flow assays have been used in rural clinics to detect dengue and Zika viruses with high sensitivity.[16]

Nonetheless, ethical aspects of data ownership, informed consent, and algorithmic bias must be addressed in order to promote equitable access and trust to AI algorithms used for diagnostics. To implement these advancements on a larger scale, collaborative frameworks between government, non-governmental organizations, and tech developers are needed.[1,5]

Comparison between traditional and AI-based viral diagnostics

Traditional viral diagnostic methods such as viral culture, PCR, and serological assays have long served as the backbone of clinical virology. These techniques offer high specificity and are well-established in laboratory workflows. However, they often suffer from limitations in speed, scalability, and real-time adaptability, especially during emerging outbreaks.[17]

In contrast, AI–driven approaches leverage computational models to analyze heterogeneous biomedical data, enabling rapid detection, automated classification, and predictive modeling. For instance, deep learning algorithms can process chest radiographs to detect viral pneumonia patterns, while transformer-based models analyze viral RNA sequences for mutation tracking and strain identification.[18]

In addition, AI systems are capable of incorporating multimodal data (real-time imaging and genomics along with clinical data) to deliver individualized diagnostic results. This integrative capacity outshines conventional approach whereby disjointed data flow is used. A real-time outbreak surveillance is also supported through AI that provides predictive insights informing the control measures taken to address a suspected outbreak.[13,19]

Although current advantages are clear, AI-based diagnostics are fraught with challenges that include algorithmic bias, data privacy issues, and regulation barriers. Consequently, a hybrid approach that unites the predictability of the conventional test with flexibility of AI could become the tool of the brightest future.[20]

Challenges in AI-based viral diagnostics

Although AI has a potential revolutionizing impact on viral diagnostics, a sufficient number of significant problems related to its use in the clinical and research environment exist.

1. Foundational AI models: need diverse, high-volume, well-labeled data to deliver generalizable performance. Nonetheless, viral diagnostic data are subject to limited recording, unbalanced classes, and inter-institutional and inter-population variability. They may predispose overfitting and/or loss of model reliability in practice.[21,22]
2. Algorithmic bias and interpretability: most of the deep learning algorithms work like a black box and hence very messy to interpret what they decide and how they make these decisions. Such a lack of transparency should create concerns regarding algorithmic bias, in cases where models are trained using data sets that represent a disproportionate set of demographics or viral strains. However, explainable AI (XAI) methods are on the rise to ameliorate the issue, although these are rudimentary and are not scalable.[23,24,25]
3. Regulatory and ethical constraints: deploying AI in clinical diagnostics requires compliance with regulatory standards, such as Food and Drug Administration or European Medicines Agency guidelines, and adherence to ethical principles surrounding patient privacy, informed consent, and data governance. These frameworks are still evolving and may lag behind technological advancements, creating bottlenecks in clinical adoption.[26,27,28,29]
4. Integration with existing clinical workflows: AI tools must be seamlessly integrated into existing diagnostic pipelines without disrupting clinical routines. This requires interoperability with electronic health records (EHRs), user-friendly interfaces, and clinician training, all of which demand significant infrastructural and educational investment.[28,29]
5. Real-time adaptability and model updating: viral pathogens evolve rapidly, requiring continuous model retraining and validation. Static models may fail to detect emerging variants or novel strains, underscoring the need for dynamic learning frameworks and real-time genomic surveillance.[30,31]

Future trends and emerging applications in AI-based viral diagnostics

The future of viral diagnostics is transforming into convergence of AI, real-time genomic surveillance, and personalized medicine. Several emerging trends can transform ways of viral infection detection and treatment.

1. Combining protein language models (pLMs): new developments in protein language models also provide proteins sensitivity to language models, using which AI systems can read viral genomic sequences more accurately than ever before. These models have the capability of predicting viral evolution, antigenic drift, and functional mutations, providing real time information of emerging variants.[26]
2. Vaccines and therapeutics: AI is emerging as a technique that can be utilized to speed up vaccine development through discovery of conserved viral epitopes and modeling immune responses. This method assists in the development of multi-epitope vaccines and personalized vaccines, in particular, to rapidly mutated viruses.[16]
3. Mobile and edge AI diagnostics: the AI models can be deployed on mobile devices- improving access to diagnostics in resource-constrained or long-distance locations. Such systems can be used to perform analysis of radiographic images or biosensor data at their site of use, with less reliance on central laboratories, thereby responding faster in the case of an outbreak.[31]
4. Predictive epidemiology and outbreak forecasting: AI-driven models are being integrated into public

health platforms to forecast viral spread, identify hotspots, and simulate intervention strategies. This predictive capability enhances preparedness and resource allocation during epidemics.[27]

5. Ethical AI and federated learning: to address privacy and data-sharing concerns, federated learning frameworks are being adopted. These models allow decentralized training across institutions without compromising patient confidentiality, paving the way for ethically robust AI deployment.[28]

Conclusions

AI is a paradigm shift in viral diagnostics due to its enhanced capabilities compared to traditional methods in terms of speed, scale and multi-source data analytics. Intelligent models have proven diagnostic accuracy in the medical applications of medical imaging, genomic analysis, and vaccine design, and have even outperformed clinical experts in some cases in particular, during epidemic emergencies or in resource-poor settings. Although these have several benefits, there are still areas of major concern when it comes to adopting these technologies fully, namely data quality, the interpretability of models, and regulatory and ethical validation. The implementation of AI in clinical practice would have to be a strong knowledge-based and regulatory framework to provide patient safety and accuracy of results. The future of diagnostics lies in the creation of explainable models, developing the remaining training dataset to reflect more geographic and biological diversity, and establishing effective lines of communication between the creators of AI and health authorities, to work collaboratively in defense of human well-being. A hybrid approach that combines traditional methods with modern algorithms may prove to be the most adaptable and beneficial strategy for addressing the increasing challenges posed by viral threats.

Conflict of interest

The authors declare that there is no conflict of interest.

Author's contributions

Ali Adel Dawood: development of the idea and overall structure, review the literature, critical analysis of conventional diagnostic techniques (viral culture, PCR, serological tests), writing of sections related to the synthesis of results, discussion, and conclusions, editing and linguistic correction.

Ahmed Mohammed Hayawi: literature analysis and synthesis of the recent developments in artificial intelligence and the purpose of viral diagnostic; writing of sections on convolutional neural networks, transformer-based models and multimodal integration; comparative analysis of traditional and AI-based systems; discussion of limitations such as data quality, algorithmic bias or regulatory compliance; contribution to the recommendation and future directions.

All authors reviewed and approved the final version of this manuscript for publication.

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Más allá de los límites del diagnóstico tradicional: el papel de la inteligencia artificial en el análisis de datos multimodales para la detección rápida de virus

Resumen

El diagnóstico preciso y rápido de las infecciones virales es fundamental para que las respuestas de salud pública sean eficaces. Este artículo revisa los métodos de diagnóstico tradicionales, incluidos el cultivo viral, la PCR y los ensayos serológicos, y destaca sus limitaciones en cuanto a escalabilidad, rapidez y adaptabilidad a los brotes emergentes. Por el contrario, la inteligencia artificial ofrece capacidades transformadoras en el análisis de imágenes médicas, secuencias genómicas y datos multimodales con una precisión sin precedentes. Las novedosas soluciones que se presentan en este artículo incluyen redes neuronales convolucionales en imágenes radiológicas, redes neuronales basadas en transformadores en biología genómica y soluciones integradas para reunir datos clínicos, moleculares y de imágenes. También se analizan los métodos emergentes, como la obtención de imágenes de moléculas individuales mediante el aprendizaje profundo y los métodos de diagnóstico basados en la inteligencia artificial con pocos recursos. Un análisis comparativo destaca las ventajas de la inteligencia artificial en comparación con los métodos tradicionales en las áreas de eficiencia, escalabilidad e integración clínica, y explora las cuestiones de la calidad de los datos, el sesgo algorítmico y el cumplimiento normativo. Por último, el artículo extrae conclusiones en las que detalla sus orientaciones futuras, los modelos lingüísticos basados en proteínas, el aprendizaje federado y las plataformas de diagnóstico portátiles. Al final, el artículo recomienda la aplicación de sistemas de diagnóstico híbridos, que combinen los enfoques convencionales con las tecnologías basadas en la inteligencia artificial, y señala que serán necesarios algoritmos interpretables y esfuerzos de desarrollo intersectoriales entre la inteligencia artificial y los profesionales de la salud para hacer frente a los nuevos retos virales.

Palabras clave: inteligencia artificial; redes neuronales convolucionales; aprendizaje profundo; virus.

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