Scripta Scientifica Medica, 2024; Online First
ISSN 0582-3250 (Print)
ISSN 1314-6408 (Online)

REVIEWS

THE INTEGRATION OF ARTIFICIAL INTELLIGENCE IN MALARIA CONTROL AND SURVEILLANCE

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ABSTRACT

INTRODUCTION: **Malaria, caused by Plasmodium spp., remains a global health challenge despite significant reductions in incidence and mortality over recent decades. Factors such as drug and insecticide resistance, diagnostic limitations, and the expansion of Anopheles vectors into new regions hinders control efforts. Artificial intelligence (AI) offers innovative tools to address these challenges by processing complex data, improving diagnostics, and supporting prevention strategies.**

AIM: **This review explores the implementation of AI-based technologies in malaria control, focusing on their roles in epidemiological surveillance, diagnosis, treatment, vector control, and vaccine development.**

MATERIALS AND METHODS: **A comprehensive literature review was conducted for studies published between 2020 and 2024. Keywords included "malaria," "Plasmodium," and "artificial intelligence," "AI." The results were reviewed, emphasizing observational research on AI applications in epidemiological modeling of malaria transmission, enhancing vector control, improving diagnostic methods and protocols, and advancing the development of new vaccines and treatments.**

RESULTS AND DISCUSSION: **AI technologies demonstrate a transformative potential in malaria control. AI-driven models can predict outbreaks by analyzing climatic, environmental, and medical data; they can improve the accuracy of rapid diagnostic tests and automate the analysis of blood smears for parasite detection, enhancing diagnostic reliability. In addition, they can accelerate drug discovery by identifying novel therapeutic targets, identify antigenic candidates, and predict immune responses assisting vaccine research. AI-integrated citizen science initiatives, supported by smartphone apps, enhances vector surveillance, while satellite imagery processed through machine learning predicts vector breeding sites.**

CONCLUSION: **AI-based tools represent a promising frontier in malaria management, offering innovative solutions for surveillance, diagnostics, treatment, and prevention. With continued research and refinement, these modern-day technologies could significantly contribute to the eradication of malaria.**

Keywords: *malaria, artificial intelligence, epidemiological modelling, surveillance*

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Received: November 8, 2024
Accepted: December 16, 2024

INTRODUCTION

The second decade of the 21st century marks a significant progress in the fight against malaria. This parasitic disease, caused by protozoa of the genus *Plasmodium*, has been absent from the map of Europe for over 50 years. Globally, its incidence has significantly decreased from 81 cases per 1,000 people at risk in 2000 to 58 in 2022. A decline in the fatality rates is also observed: from 864,000 in 2000 to 608,000 in 2022, while the number of countries with endemic malaria transmission dropped from 108 in 2000 to 85 in 2022 (1). However, the evolutionary capabilities of *Plasmodium* parasites and their vectors significantly complicate the fight against the disease. The widespread use of chloroquine and DDT in the 1950s has led to two fundamental problems—resistance of the causative agents to medications and resistance of *Anopheles* mosquitoes to insecticides. Over the past 15 years, the global use of artemisin-based combination therapy (ACT) and the mass distribution of insecticide-treated bed nets in Africa have contributed to a significant reduction in the prevalence and mortality of malaria. However, both the rapidly increasing resistance to artemisin preparations in Southeast Asia and resistance to pyrethroids in African mosquitoes have been recorded. Another challenge is the expanding uptake of new endemic areas by *Anopheles stephensi*, a vector capable of transmitting both *P. falciparum* and *P. vivax*, and resistant to common insecticides. Additionally, there is a rise in *P. falciparum* genotypes that do not express specific proteins (histidine-rich proteins 2/3, Pfhrp2/3), which are widely used in malaria testing, increasing the risk of underdiagnosis (1,2). Our unstable world—marked by pandemics, international conflicts, migration waves, and climate change—calls for innovative and original approaches to successfully address global threats like malaria. One of these can be the use of artificial intelligence (AI).

Despite the common perception of AI as a modern technology, it is actually one of the oldest fields in computer science, emerging as early as the 1950s with the idea of "machines capable of intelligent behavior." After a certain delay in the development of the area, the initial optimism and interest in AI were revived at the beginning of the 21st century with the emergence of the so-called machine learning—software that can automatically learn from past data to acquire knowledge from experience and gradually improve its performance in learning to make predictions based on new data. Subsequently, the field evolved with the development of deep learning, which is based on the creation of deep convolutional neural networks (CNNs) (3,4). These networks represent a type of deep learning algorithm applied to image processing, simulating the behavior of interlinked neurons in the human brain (5).

Epidemiology, as the science of studying the causes and control of mass disease processes (particularly infectious diseases) (6), has always relied on data traditionally obtained through observation, mathematical analysis, and statistics. In the digital era, medical professionals are receiving vast amounts of data, known as Big Data, which are characterized by the volume, velocity, and variety (commonly referred to as the three V's) which must be processed (7). Analyzing this amount of unstructured data is not achievable with traditional software, while AI serves as a powerful analytical tool that enhances and accelerates the information processing.

AIM

This review aims to demonstrate the current level of implementation of AI in the different areas of diagnosis, treatment, control, surveillance, and prevention of malaria and to present relevant examples from contemporary scientific literature.

MATERIALS AND METHODS

The Web of Science, PubMed, and Scopus databases were searched for following keywords: "malaria," "*Plasmodium*," "artificial intelligence", "AI" with the last 5 years (2020–2024) set as the period to be used. The generated lists from Web of Science (65 results), PubMed (282 results), and Scopus (75 results) were compared for repeating results and a combined list of 173 articles was collected. The scientific relevance of each publication was reviewed by the authors and applicable examples were selected to be presented in this review, including mainly observational studies analyzing AI as a tool in the epidemiological modeling of malaria transmission, vector control, improving diagnostic methods and protocols, and the development of new vaccines and treatment. All other reviews, case reports, unpublished articles, preprints, comments, letters, and editorials were excluded.

RESULTS AND DISCUSSION

The results from our literature investigation were stratified into several groups depending on the inclusion of AI-based tools for epidemiological surveillance and malaria dynamics modeling; algorithms for the collection and analysis of medical data and vector information, and AI systems assisting in the diagnosis, treatment, and prevention of malaria. Specific exemplary studies were presented to illustrate the possibilities of implementing AI in the global effort to diminish the impact of malaria on human health.

AI-Based Tools for Epidemiological Surveillance and Modeling

The ability to process large volumes of data with the help of AI has become a valuable tool in the surveillance of the spread and the modeling of the epidemic dynamics of malaria. It draws researchers' attention to hidden trends in the complex relationships between *Plasmodium* parasites, their vectors, and affected human populations, all within the context of the environmental conditions, climate, and landscape features in different geographic areas.

Using AI, scientists from Uganda (8) identified the most reliable predictors of malaria incidence and evaluated the impact of various factors on its transmission. AI algorithms have analyzed indicators such as the number of new cases, medium temperature, rainfall, anti-malarial treatments, access and use of mosquito nets, and indoor residual spraying to recognize patterns and relationships that influence the spread of the disease. By training these algorithms on previous data, they were able to predict future malaria outbreaks and the dynamics of new cases. Additionally, integrating AI with geospatial analysis allowed researchers to map malaria outbreaks, identify high-risk areas, and prioritize efforts to combat the disease. This facilitated targeted preventive interventions and the efficient allocation of resources in outbreak regions. Komugabe et al. (8) demonstrated that anti-malarial treatment was the most significant factor in reducing disease transmission. A substantial decrease in case incidence was also associated with access to mosquito nets. Moreover, it was found that higher environmental temperatures correlated with increased disease incidence. The study recommended prioritizing indoor residual spraying in areas predicted to have high incidence rates. The emphasis was that focusing on preventive measures, such as education on the use of insecticide-treated nets and long-lasting insecticidal nets, was crucial for reducing malaria transmission in Uganda (8).

Another example of integrating machine learning techniques into the epidemiological modeling of malaria spread is the study by Kabaria et al. (9), which explores and identifies environmental factors influencing the risk of disease transmission in urban areas of Tanzania. The authors used high-resolution satellite images to determine urban environmental conditions associated with malaria transmission in the city of Dar es Salaam. A higher risk of malaria infection was linked to proximity to dense vegetation, water bodies, and wetlands, while a lower risk was found in closely built-up central and administrative parts of the city. The resulting predictive maps could serve as valuable tools for epidemiological surveillance authorities to allocate more resources for vector control in targeted areas. The AI-driven modeling process developed in this study can be replicated in other urban areas to identify vulnerable regions and population groups (9).

Parselia et al. (10) have determined that, currently, more than 1,000 satellites with high spectral and spatial resolution allow the monitoring of the geographic distribution and breeding dynamics of malaria vectors. Satellite images can be used to surveil stagnant water bodies, potential breeding sites for *Anopheles* mosquitoes, as well as to track the impact of climate change on their spread. Analyzing these images with AI-based algorithms allows for the prediction of potential malaria hotspots based on environmental conditions. Satellite data also reflect human population density and agricultural activity, which also influence the spread of malaria vectors.

Some other examples in using AI-based systems in malaria epidemiological modeling are demonstrated by other studies—machine learning predicting malaria epidemics in Burkina Faso (11) and future outbreaks in Limpopo (South Africa) by assessing historical epidemiological data in correlation to climate conditions (drought indices) (12). Artificial neural networks were used to simulate the probable impact of climate change on malaria incidence (13) and to develop propagation models of malaria infection using data sets from the population characteristics of mosquitoes and humans (14). Geospatial information analyzed by CNNs was applied in the extrapolation of the future spread of one of the zoonotic species, *Plasmodium knowlesi*—a new and emerging threat for human infections (15).

◈ AI algorithms for the collection and analysis of medical data

The electronic health record (EHR) is a digital resource that collects information about a patient related to their past, present, or future physical and mental health or state, stored in an electronic system(s) used for receiving, transmitting, storing, retrieving, and manipulating multimedia data, with the primary goal of providing healthcare and health-related services (16). Each record includes personal information about the patient, details on medical examinations, tests, therapy, as well as sociobehavioral and epidemiological information. Reports indicate that the volume of this valuable data in the United States alone has already reached a zettabyte (10^{21} gigabytes), making it difficult to structure and analyze (7). The integration of AI in the analysis of the data stored in EHRs can assist healthcare professionals in identifying risk factors for communicable diseases (including malaria) and offer prognoses and solutions for prevention and treatment. The rapid processing of EHR data can provide insights into the emergence of new malaria outbreaks by simultaneously registering multiple records in a specific geographic area. Such early detection can be crucial in preventing the spread of the disease, minimizing the impact on public health (17). Moreover, by analyzing patient examination data, AI algorithms can detect deviations from the standard course of the disease, providing timely alerts about the emergence of new malaria strains resistant to antimalarial treatments. This approach could serve as the foundation for creating real-time malaria monitoring and control systems, evolving from systems based on periodic reports. For instance, based on patients' previous history of malaria Bria et al. have developed machine learning-based symptom classifiers that can be used in the clinical practice in the endemic countries (18). Other studies demonstrate the possibility of interpreting data from basic laboratory hematological tests (hemoglobin, platelet counts, red blood cell counts, lymphocyte counts, and percentages) analyzed through AI systems to forecast disease outcomes (19) or to separate quickly and efficiently malaria from non-malaria pediatric patients (20).

Additionally, AI-based systems can integrate information from various sources, such as social media, news reports, and even online search trends. The ability to analyze such diverse data in real time provides a more comprehensive view of the health landscape, capturing early signals of infectious disease outbreaks that may be missed by conventional methods (21).

Malaria control has been shown to be weak among communities that lack knowledge about an infection's risks and potential preventive measures. AI-driven communication strategies represent an innovative approach to enhance community engagement and education. AI-powered chatbots can provide accurate and up-to-date information about malaria, interacting with individuals through various platforms, including social media and messaging applications, offering personalized guidance on preventive measures. AI-driven social media analyses can also monitor public attitudes and identify areas where targeted health education campaigns are needed, ensuring that accurate information reaches the vulnerable populations (21).

◈ AI algorithms for the collection and analysis of vector-related data

Improving malaria control can be achieved through the integration of AI into so-called *citizen science* or *community monitoring*, which involves the public in scientific research by through data collection. A great example is the active participation of citizens in entomological studies through their smart devices, which can provide valuable information about the bionomics of *Anopheles* mosquitoes, saving significant resources for infection control authorities and reaching the most remote areas (22). Various international projects, such as Mosquito Alert, GLOBE Observer, and iNaturalist, are available as mobile apps, with iNaturalist alone accounting for 121 million registered observations since its launch. To analyze and accurately identify mosquitoes, scientists use CNNs, and the data collected is then processed by entomology specialists (23–26).

◈ AI systems assisting the diagnosis of malaria

Effective malaria control cannot be achieved without efficient diagnostics. Due to their accessibility and ease of use in first line and field settings, rapid antigen tests are widely implemented. However, basic rapid diagnostic tests (RDTs) are sometimes misinterpreted, reducing their reliability for medical treatment. In this regard, Gupta et al. (27) have devised an AI-based system that can be used in low-income settings (offline, on mobile phones with low memory capacity) to provide accurate and consistent result interpretation of the RDT and increase their trustworthiness.

However, the gold standard for confirming malaria remains microscopic visualization and morphological identification of the specific *Plasmodium* species through the examination of thick and thin blood smears, conducted by highly specialized diagnosticians. To complement existing tools, new diagnostic methods based on deep learning and automated neural network techniques are being developed. These methods aim to visualize and analyze digital images of blood smears to detect malarial parasites, to recognize their stage-specific morphology, to assess the parasitemia levels and to automate (to some extent) this time-consuming diagnostic process (28–31). Future smartphone applications integrating AI-based image analysis could serve as an affordable option for quick and reliable diagnosis in resource-poor, malaria-endemic regions (32,33).

- **AI-tools in analyzing genetic data and assisting drugs and vaccine development**

A thorough understanding of the genetic variations of *Plasmodium spp.* and the mechanisms driving drug resistance can be achieved through genome sequencing, replacing the existing targeted genotyping of drug resistance loci (34). The multidisciplinary team of MalariaGEN, which includes bioinformaticians, data scientists, statisticians, and geneticists, transforms raw genomic sequences into high-value data resources ready for analysis (35). The data generated by the project and structured with the help of AI has become a key resource for the epidemiology studies of plasmodia distribution (36). The genome data is essential for antimalarial drug resistance studies, discovering new genetic markers and mechanisms of resistance through genome-wide association protocols and combined analysis of genomic and transcriptomic data. The information is also used to investigate gene deletions responsible for the expression of *P. falciparum* histidine-rich proteins (Pfhrp2/3), resulting in failures of rapid antigen tests. The genome analysis allows for a more in-depth examination of host-parasite interactions and the description of the evolutionary adaptation and diversification of local parasite populations (35).

The genomic approach is also applied in testing new candidates for antimalarial vaccines, the search for which has continued for decades. Currently, the World Health Organization recommends only one vaccine (RTS,S/AS01) for the prevention of *P. falciparum* malaria in children living in regions with moderate to high transmission. Several other vaccines, currently in clinical trials, aim to target different phases of the parasite's life cycle (1). Alongside efforts to optimize suitable vaccine candidates, researchers continue to develop and utilize advanced technologies such as bioinformatics and immunoinformatics, representing computer science and biology synthesis. The research in these fields intends to devise innovative vaccination strategies. AI algorithms can help by analyzing vast databases of genomic and proteomic sequences to identify potential vaccine targets and determine the most promising candidates for further testing. AI algorithms also interpret chemical information related to biological systems, evaluating the binding affinity of potential epitopes to human leukocyte antigen (HLA), aiding in the selection of epitopes that can effectively engage the immune system and filtering out ineffective candidates, thereby saving significant time (37,38). Additionally, AI-based approaches are used to predict the immune response during vaccination. This is done using agent-based models, which are computational models that simulate the behavior and interactions of individual agents within a system. They can capture and replicate the complex interactions and dynamics of the immune system at various levels, from individual cells to tissues and organs, simulating how different vaccine components affect specific elements of immunity (39).

The growing resistance of *Plasmodium* species to existing antimalarial drugs makes the search for new therapeutic options urgent and critical. The traditional process of discovering bioactive molecules is time-consuming and costly. By analyzing vast biochemical libraries in search of potential antimalarial compounds that act against specific parasite proteins, AI algorithms can accelerate and refine the development of new treatment agents and combinations for malaria (40–43).

❖ Concerns and limitations in AI application in medical studies

Despite the proven benefits and promising results from the use of AI in malaria control and surveillance, certain limitations remain. Chief among them are concerns regarding the quality, quantity, and diversity of the data used to train AI algorithms. Medical professionals require carefully selected datasets for the clinical and technical validation of AI models. Additionally, training AI programs on insufficiently diverse data may limit the generalizability of results across different patient populations or geographic regions, reducing their applicability in various healthcare settings due to potential biases and decreased accuracy (44). Even with a properly curated dataset, there is a risk that AI models may function as a black box, meaning they are opaque regarding how conclusions are drawn and predictions made—this is particularly true for self-learning AI algorithms. In modern evidence-based medicine, both doctors and their patients are rightfully wary of using non-interpretable AI models (45). Another limiting factor involves ethical policies and concerns regarding patients' consent for the use of their health and personal information. Furthermore, the implementation of AI-based technologies in clinical practice may require significant financial investments and specialized infrastructure, which may not be feasible for all healthcare systems, especially in poorer regions that are predominantly affected by malaria (44). Addressing these concerns is crucial to ensure the responsible and effective integration of AI into infectious disease control and surveillance, particularly for malaria, in order to limit its spread and potentially eliminate it while maintaining patient safety and ethical standards.

CONCLUSION

Throughout its history, humanity has constantly been facing various challenges and threats: climatic, demographic, and infectious. Overcoming them requires unconventional solutions and innovative approaches. In this review, we have presented some of the prominent examples from the recent five years and the range of possibilities of inclusion of AI-based technologies (deep learning, neural networks, etc.). By developing and utilizing the tools provided by the modern world, we can maximize our efforts in trying to estimate the current spread and impact of this disease and, more importantly, to predict and prevent future outbreaks, assessing the intricate connections between environmental factors, human and vector populations. The AI-enhanced epidemiological surveillance systems can be applied directly in the field by efficient medical resource allocation in high-risk areas. AI-driven analysis of EHRs aids in early detection of outbreaks and identification of drug-resistant strains. Citizen science initiatives, supported by AI, contribute valuable data on vector bionomics and distribution. AI systems assist in improving the accuracy, consistency, and reliability of RDTs and microscopic examinations. In genomics, AI facilitates the analysis of *Plasmodium* genetic variations, supporting drug resistance studies and vaccine development. AI accelerates the discovery of new antimalarial compounds by analyzing vast biochemical libraries. Despite these promising applications, limitations and concerns persist. These include issues related to data quality and diversity, the interpretability of AI models, ethical considerations regarding patient data usage, and the financial investments required for implementation. Another important obstacle is the need to apply these advanced technologies in the low-resource settings of the developing countries that are mostly affected by malaria. In conclusion, while AI presents innovative solutions for combating malaria, its successful integration into global malaria control efforts will require addressing these challenges. Future research should focus on refining AI models, ensuring data quality and diversity, and developing ethical frameworks for AI use in healthcare. As the cutting-edge AI technologies continue to evolve, their role in malaria management is likely to expand, potentially contributing significantly to the global goal of eradicating one of the oldest and deadliest diseases on the planet.

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