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The Application of Artificial Intelligence in Addressing Biothreats

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Abstract

The advent of new technologies, particularly artificial intelligence (AI), has expanded the array of options and enhanced performance in addressing biothreats. This article provides a comprehensive overview of the specific applications of AI in addressing biothreats, aiming to inform and enhance future practices. Research indicates that AI has significantly contributed to infectious disease surveillance and emergency responses, as well as bioterrorism mitigation; despite its limitations, it merits ongoing attention for further study and exploration. The effective deployment of next-generation AI in mitigating biothreats will largely hinge on our ability to engage in continuous experiential learning, acquire high-quality data, refine algorithms, and iteratively update practices. Meanwhile, it is essential to assess the operational risks associated with AI in the context of biothreats and develop robust solutions to mitigate potential risks.

Biological threats have become global, complex, and diversified. The concept of biothreat has continued to evolve to include natural, accidental, and intentional threats and their social, economic, political, and security consequences; exploitation of biotechnologies for malicious and/or military use; and unauthorized access to biological data.[1] The acceleration of global integration has greatly increased the speed and scope of epidemic, and the rapid development of biotechnology also provides more possibilities for the research and development of biological weapons. Therefore, preventing and responding to biothreats has become an important task for governments and the international community. New technologies and breakthroughs represented by artificial intelligence (AI) have provided more options and played a better role in addressing the threats.[2–4]

The field of AI was launched in 1956 by a group of computer scientists at a symposium at Dartmouth College. Experts will try to figure out how to get machines to use language, form abstractions and concepts, solve various problems that currently only humans can solve, and improve themselves. The research assumes that every aspect of learning or any other feature of intelligence can in principle be described so precisely that a machine can simulate it.[5] AI, machine learning (ML), and deep learning (DL) are interrelated yet distinct domains. AI encompasses a broad spectrum of technologies aimed at developing intelligent systems capable of executing tasks that typically necessitate human cognitive abilities, such as learning, problem-solving, and decision-making. ML represents a specialized area within AI focused on training computational models to perform tasks autonomously by leveraging patterns and insights derived from data. DL constitutes a further subset of machine learning that employs multi-layered artificial neural networks for advanced learning and decision-making processes.[3] The significance of AI technologies is increasingly acknowledged as pivotal in transforming human society; these tools can now discern complex and previously obscured data structures while offering innovative solutions to longstanding challenges. Collectively, these advancements hold the potential to significantly enhance biosecurity initiatives.

How AI can be applied to biothreat response requires a systematic review of experiences to guide subsequent practices. Previous studies have largely concentrated on exploring how AI can potentially amplify biothreats,[6,7] while relatively limited effort has been devoted to comprehensively synthesizing the positive contributions of AI in addressing such threats. In this review, we summarize the role of AI in the monitoring of emerging infectious diseases and the response to emerging infectious diseases and bioterrorism, and, finally, we discuss the key limitations of AI in biothreat, addressing applications and important considerations for future improvements.

Surveillance

The utilization of AI in the surveillance and early warning of emerging infectious diseases has demonstrated significant efficacy.[8–12] During the Covid-19 pandemic, we observed the deployment of numerous AI solutions aimed at addressing the crisis, which demonstrated remarkable efficacy. AI-driven algorithms possess the capability to analyze, filter, classify, and aggregate signals related to infectious disease events from textual data with unprecedented speed and accuracy. HealthMap serves as a notable example of this success;[13-16] HealthMap employs natural language processing technology to identify signals of infectious disease outbreaks in real-time by analyzing online text against established pathogens and geographic regions. It utilizes a Bayesian machine learning classification framework to distinguish outbreak-related information from other health reports, such as scientific publications and vaccination initiatives. Additionally, HealthMap automatically extracts geographic data to connect multiple reports, thereby preventing the oversight of disease clusters across different jurisdictions. Researchers have leveraged official health reports, internet search trends related to COVID-19, news media coverage, and various datasets to generate daily forecasts of COVID-19 activity through a meta-population model that incorporates ML techniques like clustering and data augmentation. This approach has achieved predictions with a 2-day lead time for COVID-19 cases while demonstrating superior performance compared to baseline models, thus significantly aiding decision-makers in implementing effective infectious disease surveillance and prevention strategies.[10] AI has demonstrated significant efficacy in monitoring epidemics within hospital settings. Sundermann and colleagues reported the development and implementation of a health care-associated transmission enhancement detection system (EDS-HAT). This system integrates ML with whole-genome sequencing (WGS) to monitor infections, thereby identifying potential outbreaks and transmission pathways that might otherwise go undetected. The findings indicate that real-time ML, leveraging electronic medical records alongside WGS, has successfully mitigated up to 40% of hospital-acquired infections across 9 hospitals affiliated with the University of Pittsburgh, resulting in substantial cost savings for these institutions.[17]

Various pathogens can elicit comparable symptomatology, exemplified by respiratory manifestations associated with rhinovirus, adenovirus, and influenza virus. Dependence on simplistic syndrome definitions may result in erroneous outbreak identification, particularly when pathogens exhibit overlapping symptoms and transmission pathways. It is imperative to accurately identify the causative pathogen of an outbreak to enable public health authorities to implement precise and effective interventions. Currently, AI offers a promising approach for distinguishing between diverse pathogens or identifying concerning mutation characteristics to enhance infectious disease surveillance.[13,18] Convolutional neural networks (CNNs) represent a sophisticated AI algorithm characterized by a highly interconnected architecture inspired by the human visual cortex, demonstrating exceptional proficiency in image classification.[19] During the supervised training phase of CNNs diagnostic interpretation, an extensive dataset of human-classified images is utilized as input. The algorithm systematically classifies each image and evaluates its accuracy against human classifications. Through iterative refinement, the CNNs adjusts its neural network parameters thousands or even millions of times to enhance its precision. Upon completion of training, the AI analyzes smear samples and presents diagnostic images for technician review while executing probabilistic differential staining diagnoses. For instance, an analysis may yield a 90% probability that an image depicts Gram-positive cocci and a 10% likelihood that it represents Gram-positive streptococci. With further training, distinctions in organism morphology can be elucidated; for example, identifying Gram-positive diplococci may indicate pneumococcus infection, whereas short Gram-positive filamentous bacteria could suggest Listeria presence or microscopic Gram-negative cocci might imply Brucella or Francisella infections.[20]

Pandemic Management

AI technologies can play a pivotal role in managing emerging infectious diseases by facilitating the allocation of emergency resources,[21] mitigating cross-border infection risks,[22] and enabling comprehensive epidemic control strategies.[23,24] Researchers employ ML techniques to predict key populations at risk of infection by integrating geographic reference data with demographic and occupational characteristics, self-reported symptoms, and information regarding whether participants are health care professionals or have had contact with infected individuals, all gathered through smartphone applications. By generating epidemic risk maps for new infectious diseases based on predicted infection risks among these key populations, policymakers can identify regions with elevated probabilities of positive test results and formulate more effective testing and disease control policies, thereby optimizing the allocation of emergency health resources.[21]

Eva exemplifies the application of AI reinforcement learning and enhanced real-time data during the COVID-19 pandemic to safeguard public health. This system aggregates cross-border travel and demographic information from individuals, integrating prior travelers' test results to assess infection risk for incoming travelers, thereby providing decision support for resource allocation in testing and subsequent infection risk management. The number of undetected infected individuals identified by Eva is 1.85 times greater than that detected through random monitoring tests.[22] In China, particularly during the COVID-19 pandemic, AI and ML technologies have been extensively employed for disease management.[23] The Internet of Things (IoT) facilitates communication with personal smartphones through Bluetooth or Wi-Fi connectivity. The associated database encompasses various types of information, including household registration details, pharmaceutical purchase records, medical histories, and travel itineraries. Passive data collected from the smartphone is integrated with actively reported information provided by users and subsequently displayed in a dedicated application or transmitted to cloud storage. Advanced AI algorithms and big data analytics are employed on the cloud-based data to generate predictive models, visualizations, or decision support tools. This processed output can then be relayed back to users via mobile applications or websites accessible to them while also being made available to authorized personnel as needed. Internet hospitals offer consultation and medication delivery services predicated on remote health care practices, with fees eligible for reimbursement through medical insurance schemes. Collaborative efforts between governments and health care institutions alongside social media platforms aim to mitigate misinformation while ensuring the dissemination of reliable health-related content. By integrating self-reported health statuses with passive background data, an infection risk scoring system—a health QR code—is established within widely utilized mobile applications such as Alipay and WeChat. Citizens are required to present a "green" code when accessing public facilities, workplaces, educational institutions, or during travel.[23]

Chatbot Generative Pre-trained Transformer (ChatGPT) is an important AI with the ability to simulate professional medical literature.[25] Prior research has demonstrated that ChatGPT possesses a robust comprehension of public health, infectious diseases, the COVID-19 pandemic, and vaccines, thereby assisting medical educators, scholars, and health care professionals in enhancing their understanding of related knowledge[26]. ChatGPT, functioning as an AI language model, is capable of disseminating precise and current information regarding infectious diseases to the public, health care professionals, and policymakers. It can be trained to monitor news outlets and social media platforms for early detection of outbreaks or disease clusters, thereby alerting health authorities to potential threats.[27] While ChatGPT may not consistently align with expert decisions in clinical case management, it demonstrates strong performance in addressing theoretical inquiries and holds promise as a valuable tool for infectious disease education and preliminary analysis.[28] Nevertheless, the precision of ChatGPT's responses in specific medical specialties remains suboptimal, and it cannot fully supplant the expertise and professional acumen of health care practitioners. Consequently, its application should be approached with caution.[29–31] Furthermore, its inherent lack of human interaction implies that while it can deliver prompt answers to inquiries, it fails to replicate the essential value of interpersonal engagement in addressing infectious diseases.

Furthermore, AI has assumed a pivotal role in the management of plant diseases. By integrating AI with real-time imaging from drones, it can facilitate the precise and targeted application of pesticides, thereby minimizing the risk of contamination to crops, livestock, humans, and aquatic ecosystems. Advanced computer vision and AI technologies can assess various attributes of plants—including maturity, disease presence, defects, size, shape, and color—thereby enabling efficient sorting and grading of agricultural products while discarding those that do not meet established criteria. This approach surpasses human observational precision.[32,33]

Addressing the Threats Posed by Bioterrorism

Biological warfare (BW) is defined as the intentional deployment of biological agents—including bacteria, viruses, fungi, and toxins—as weapons in military conflicts, while bioterrorism pertains to the use of these agents against civilian populations.[34] This form of dissemination is motivated by ideological objectives—whether political or religious—with the aim of inducing panic, causing mass casualties, or inflicting economic damage. These biological agents may occur naturally or be genetically engineered to enhance their potential for widespread transmission.[35] AI is increasingly recognized as a valuable asset in the monitoring, management, and response to biothreat events, demonstrating significant potential for enhancing biothreat oversight.[36] Techniques such as deep learning analysis and natural language processing can produce both extracted and abstracted summaries from documents containing conflicting information. These analytical methods are capable of autonomously accessing and organizing data, translating information across various languages, and alleviating human cognitive load while minimizing errors. Furthermore, AI algorithms can be employed for biothreat risk assessment; these algorithms possess the ability to learn, adapt, and evolve in response to emerging threats, thereby facilitating near real-time policy evaluation and adjustment.[4,37]

The future of biotechnology is significantly influenced by the potential for both accidental and intentional misuse. A reliable identification of the distinct characteristics associated with various gene designers, referred to as "genetic engineering attribution," can serve as a safeguard against such abuses, with ML offering valuable contributions in this domain.[38,39] Researchers employed a biologically inspired methodology that integrates the learning of DNA building blocks, basic phenotypic data, and recurrent neural networks (RNNs), achieving over 70% accuracy in lab-of-origin attribution within a model scenario utilizing data from Addgene, the world's largest plasmid repository. In this model context, research laboratories deposit DNA sequences and associated phenotypic metadata on Addgene to engineer organisms and disseminate their genetic designs with the broader scientific community. Conversely, in deployment scenarios, unidentified genetically engineered organisms may be sourced from environmental samples, laboratory accidents, misuse incidents, or contentious authorship cases. By characterizing these samples through sequencing and phenotypic experimentation in controlled environments, researchers can ascertain both the engineered sequence and its corresponding phenotypic attributes. Subsequently, this information is fed into an attribution model designed to predict the likelihood that an organism originated from a specific individual linked to known laboratories, thereby, facilitating further conventional investigations. The study illustrates that straightforward models can effectively predict national-state affiliations as well as ancestral lab origins, laying groundwork for an integrated attribution toolkit aimed at fostering responsible innovation and enhancing international security. However, it emphasizes that while achieving 70% accuracy in lab-of-origin attribution is significant, actual investigative outcomes will largely hinge on human expertise necessitating multidisciplinary collaboration.[39]

The Biosecurity Artificial Intelligence Network (BAIN) is capable of screening all commercial nucleic acid sequences, including gene fragments and oligonucleotides, as well as peptide sequences, utilizing genomics and proteomics data from databases encompassing known pathogens, toxic peptides, and proteins. BAIN will leverage ML algorithms to incorporate computer bioactivity predictions into screening procedures. These predictions facilitate the identification and annotation of potentially toxic or hazardous gene products for further investigation. A key innovation introduced by BAIN in the realm of biosecurity is its capacity to aggregate customer profiles, orders, and screening outcomes while establishing a user network that can utilize data and web scraping tools provided by users to categorize each user's research domain. Personal affiliations and research groups can be compiled to construct a map of researcher networks, thereby assisting BAIN in identifying anomalous situations. Furthermore, BAIN will correlate primers along with other nucleic acid and peptide synthesis requests from institutional or research network nodes to detect intentionally obfuscated potential malicious nucleic acid or peptide synthesis orders. All risk signals identified by BAIN will undergo evaluation by subject matter experts before being recommended for appropriate subsequent actions. However, it is important to note that BAIN cannot screen synthesis products generated independently without commercial synthesis providers (such as portable synthesizers) or through extraction and purification from natural or biotechnological sources; nor can it identify sequences not submitted within its supplier network. Nonetheless, BAIN offers a conceptual framework aimed at enhancing biosecurity for commercial synthesis providers and users alike, which may serve as an effective deterrent.[40]

Limitations

The decision-making processes of AI systems primarily rely on algorithms and data; however, if the data are incomplete or the algorithm is inappropriate, this can result in biases and discrimination within the decision-making framework of AI systems,[2]

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potentially leading to false alarms or failures in identifying critical epidemiological signals.[41] AI models—especially in emergency scenarios such as pandemics or bioterrorism—often operate with sparse, noisy, unstandardized, or biased data. The lack of representative data, especially from marginalized populations, may compromise the accuracy and generalizability of these models. An analysis of COVID-19 mortality data from the US revealed that due to insufficiently coded racial information in the surveillance database, there were discrepancies in mortality rates among Black and Hispanic patients, resulting in an underreporting of mortality rates by as much as 60%.[42]

Data privacy represents a critical concern that necessitates careful consideration in the deployment of AI technologies. Tools such as health QR codes, smartphone geolocation, and social media monitoring, although useful for outbreak containment, raise concerns about excessive data collection and the non-consensual use of personal information, potentially violating privacy and informational self-determination principles. In the realm of infectious disease monitoring, wearable health technologies, connected health devices, and smartphones linked to open social media platforms furnish AI companies with vast amounts of data.[43] However, these companies frequently exhibit a lack of transparency regarding their data utilization practices and tend to excessively collect users' private information, thereby heightening the risk of data breaches. It is imperative for governments and regulatory bodies across various nations to enhance the framework of laws and regulations aimed at safeguarding data privacy by clearly delineating standards for data collection, processing, and storage applicable to enterprises. Concurrently, AI firms should implement advanced encryption techniques, anonymization processes, and other technological measures to ensure the protection of user data, privacy, and security. Additionally, it is essential to bolster system security capabilities to mitigate risks associated with hacking attempts and potential data leaks.

The development of AI has reshaped the threat landscape of biological hazards, presenting challenges. While AI has the potential to provide innovative solutions, concerns arise about its misuse in the creation of biological weapons. The convergence of AI with gene editing has sparked biosafety concerns, as it may expedite the research and development of dangerous pathogens and amplify the risks associated with their malicious manipulation. To address these challenges, the advancement of biotechnology necessitates preventive and regulatory measures. Expert recommendations emphasize the need for solid regulations and responsibility of creators, demanding a proactive, ethical approach and governance to ensure global safety.[6]

AI cannot entirely supplant the expertise and multidimensional collaboration inherent to professional personnel. For instance, the accuracy of ChatGPT's responses in health care remains suboptimal, failing to fully substitute for the knowledge and specialized skills possessed by medical professionals. Effective cross-jurisdictional and cross-functional coordination is essential for harnessing collective wisdom in addressing new and emerging diseases.[13] The intersection between AI and biothreats delineates a complex domain, demanding not only technological advancement but also ethical deliberation and adaptive governance. Regulatory mechanisms must be dynamic and risk-based, with multisectoral participation (scientists, governments, civil society) and continuous assessment to proactively mitigate potential threats amidst accelerating technological evolution. Biosecurity pertains to the welfare of all humanity; thus, a concerted effort among nations is imperative to establish international coalitions to develop, share, and monitor AI technologies aimed at global health and biothreat prevention. Future studies could focus on the creation of AI governance models in public health emergencies, including criteria for scientific validation, ethical use, and accountability protocols. Research aimed at making AI models more transparent, auditable, and understandable to non-technical professionals is critical for large-scale adoption.

Conclusions

The future response to biothreats will be defined by the advent of emerging technologies, such as AI, biotechnology, and quantum computing, which will offer novel approaches for addressing these challenges and enhancing operational efficiency. Research indicates that AI has significantly contributed to infectious disease surveillance and emergency response efforts, including those related to bioterrorism; however, its efficacy is not without limitations and necessitates ongoing scrutiny and further investigation. The successful integration of next-generation AI in responding to biothreats will largely hinge on the ability of relevant personnel to continuously learn from experience, acquire effective data sets, optimize algorithms, and iteratively refine practices. Furthermore, it is essential to identify operational risks associated with AI in the context of biothreats. We must develop, share, and monitor AI technologies aimed at global health and biothreat prevention, guiding research toward the development of robust solutions that protect global security against societally catastrophic risks.

Competing interests. The authors declare that they have no competing financial interests.

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