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Exploring the Potential of Artificial Intelligence and Machine Learning to Combat COVID-19 and Existing Opportunities for LMIC: A Scoping Review

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Abstract

Background: In the face of the current time-sensitive COVID-19 pandemic, the limited capacity of healthcare systems resulted in an emerging need to develop newer methods to control the spread of the pandemic. Artificial Intelligence (AI), and Machine Learning (ML) have a vast potential to exponentially optimize health care research. The use of AI-driven tools in LMIC can help in eradicating health inequalities and decrease the burden on health systems. **Methods:** The literature search for this Scoping review was conducted through the PubMed database using keywords: COVID-19, Artificial Intelligence (AI), Machine Learning (ML), and Low Middle-Income Countries (LMIC). Forty-three articles were identified and screened for eligibility and 13 were included in the final review. All the items of this Scoping review are reported using guidelines for PRISMA extension for scoping reviews (PRISMA-ScR). **Results:** Results were synthesized and reported under 4 themes. (a) *The need of AI during this pandemic*: AI can assist to increase the speed and accuracy of identification of cases and through data mining to deal with the health crisis efficiently, (b) *Utility of AI in COVID-19 screening, contact tracing, and diagnosis*: Efficacy for virus detection can a be increased by deploying the smart city data network using terminal tracking system along-with prediction of future outbreaks, (c) *Use of AI in COVID-19 patient monitoring and drug development*: A Deep learning system provides valuable information regarding protein structures associated with COVID-19 which could be utilized for vaccine formulation, and (d) *AI beyond COVID-19 and opportunities for Low-Middle Income Countries (LMIC)*: There is a lack of financial, material, and human resources in LMIC, AI can minimize the workload on human labor and help in analyzing vast medical data, potentiating predictive and preventive healthcare. **Conclusion:** AI-based tools can be a game-changer for diagnosis, treatment, and management of COVID-19 patients with the potential to reshape the future of healthcare in LMIC.

Keywords

artificial intelligence, machine learning, COVID-19, pandemic, low middle-income countries

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Introduction

Dr. Tedros Adhanom Ghebreyesus, director-general of the World Health Organisation (WHO), declared the COVID 19 a global pandemic on March 11th, 2020.[1] Since then, it has become a global public health crisis and has negatively impacted the global economy. Failure of the existing health systems to prevent massive disruption caused by COVID-19 has emphasized a need to develop newer methods to control the spread of such pandemics.

Artificial Intelligence (AI) is defined as the study of "intelligent agents," which are devices that "perceive their

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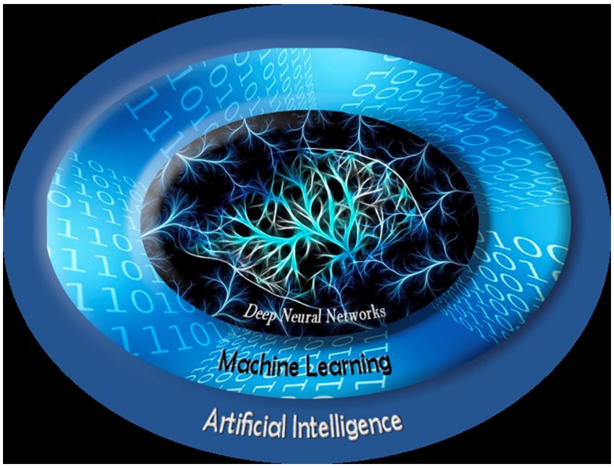

Figure 1. AI, ML, and deep neural networks: The relationship.

environment and take actions to maximize their chance of success at some goal."[2] A subset of AI is Machine learning (ML), which learns from trial and error basis and improves its performance on the results. ML has continued to show promising results in optimizing processes and resource allocation and preparing new data using versatile methods.[3,4] Deep learning, a subset of ML, uses neural networks, which are one of the most beautiful programming paradigms ever invented (Figure 1). Neural networks specifically and artificial intelligence in general have a vast potential to exponentially optimize health care research, especially in an ongoing pandemic where time is of the essence. Clinical data, epidemiological data, and genetic data have to be all processed together to come up with the best possible prevention, diagnosis, and management of disease, and extrapolate it to public health measures.[5,6] To tackle such variations, there is a high need for precise and integrated command and control system, and ML brings a solution to all these complex problems.[3]

This pandemic has put immense pressure on authorities to gather clinical, epidemiological, and public health data on coronavirus, and use it optimally to take appropriate and timely actions to control its spread, with minimum disruption of the economy and people's lives. Artificial Intelligence-driven tools have a great potential to make this process effortless, and arguably much better as compared to humans.[7] One example is real-time data sharing through dashboards that have helped in understanding the spread of SARS-CoV-2 coronavirus and assisted authorities to take measures to protect their communities. Machine learning algorithms have been put in place for the screening of SARS-CoV-2 assay through the use of a CRISPR-based virus detection system, which demonstrated high sensitivity and speed.[8,9] For the screening of COVID-19 patients on large scale, Neural Network classifiers have been developed based on the patient's distinct respiratory pattern.[10] AI is not limited to screening patients but also assisting in therapeutics and treatment of COVID-19. AI has been incorporated in running clinical trials that test for the effectiveness of existing treatments against SARS-CoV-2.[11] Additionally, to propose and generate novel drug-like compounds against SARS-CoV-2, a deep learning-based drug discovery pipeline is being used.[12]

Most of these artificial intelligence-driven tools are seen to been reinforced and practiced in high-income countries. While in LMIC, there is still a lack of evidence on the use of artificial intelligence in the prevention, diagnosis, and treatment of the COVID-19 pandemic. AI use in LMIC can help in eradicating health inequalities and reduce the burden on the health care systems.[13] AI-based tools are already being explored to be used in LMIC, to ease the burden on resource-limited settings to improve outcomes.

Our Scoping Review aims to explore the use of AI and ML to combat COVID-19 and opportunities for LMIC to adapt and implement from these AI-driven tools to their settings for better outcomes and response to this COVID-19 pandemic.

Methods

This Scoping Review was drafted using the Preferred Reporting Items of Systematic Reviews and Meta-Analysis (PRISMA) guidelines and its extensions for scoping reviews (PRISMA-ScR).[14]

Literature Search Strategy

The literature search was conducted on PubMed for all the articles relevant to the scope of our research question from December 2019 till April 2020 for a period of 3 weeks. The Keywords were searched using Boolean operators "OR/AND." The search terms were: ("2019-nCoV" OR "coronavirus" OR "COVID-19" OR "nCoV)" AND ("AI") OR "Artificial Intelligence" AND ("ML") OR "Machine Learning" AND "(LMIC)" OR "Low middle-income countries"). The literature search fields for keywords included Title, Abstract (Summary), and Keywords of the articles.

Eligibility Criteria

All articles related to Artificial Intelligence (AI) or its subset (Machine learning, Deep Neural Networks) and clinical, epidemiological, or public health aspect of COVID-19 were included. Articles related to basic sciences and phylogenetics of COVID-19 were excluded. All non-English articles were excluded as well.

Selection of Sources of Evidence

The studies were selected through an independent literature search by two separate reviewers, RA and MN. After identifying and removing the duplicate articles data extraction and synthesis was performed. All reporting was done following the PRISMA flow diagram (Figure 2).

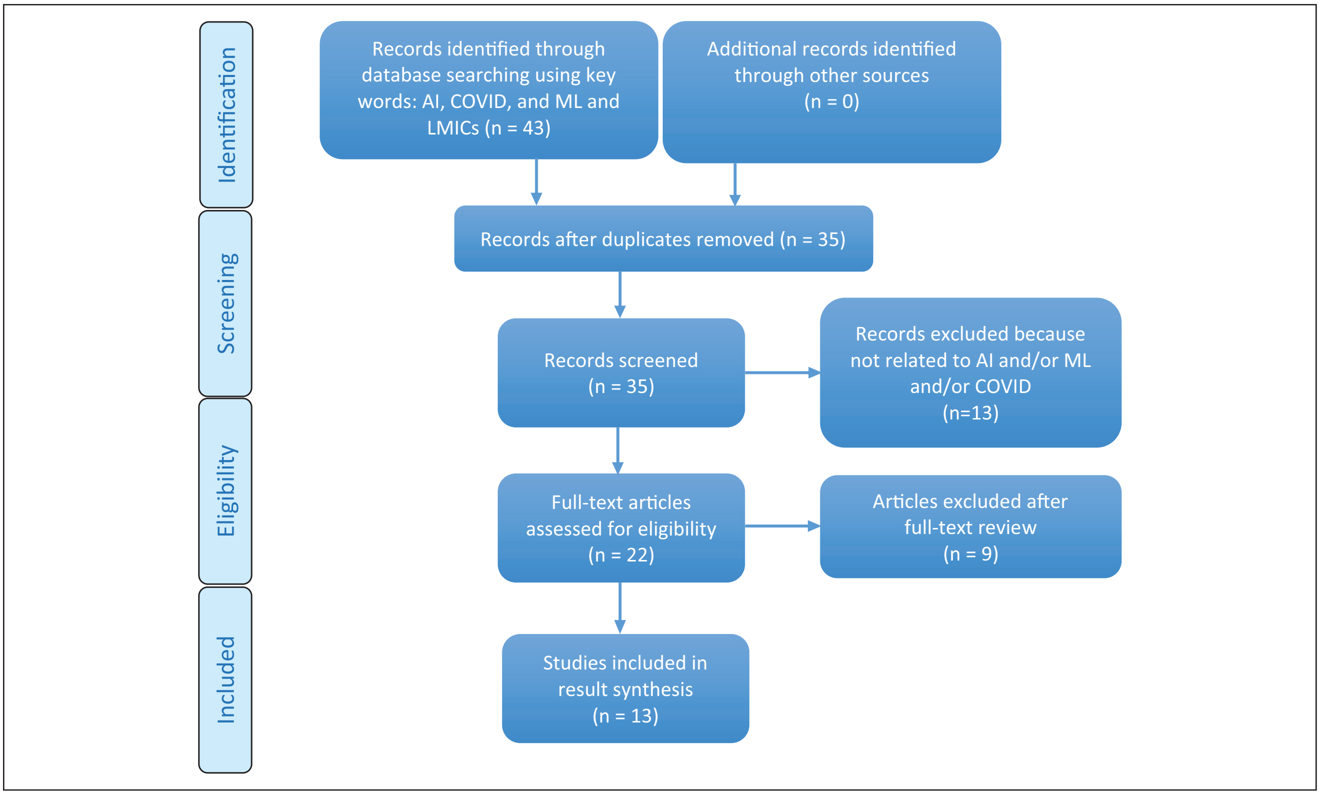

Figure 2. PRISMA flowchart.

Data Charting Process

All the included articles were listed in a table form reporting study title, date of publication, journal of publication, and key findings of all included studies were tabulated (Tables 1 and 2). While doing data charting, the following data items were extracted: Study design, Data sources for AI development or evaluation, category of AI, included intervention/s, country of study, study aims, and study findings (results)

Synthesis of Results

Results of the study were synthesized based on formulated 4 themes(categories) identified through literature review following PRISMA guidelines of result reporting and synthesis. The articles were grouped based on these 4 themes: *COVID-19 pandemic and the need of AI*, *Utility of AI in COVID-19 screening, contact tracing and diagnosis, Use of AI in COVID-19 patient monitoring and drug development, AI beyond COVID-19 & opportunities for Low-Middle Income Countries (LMIC).*

Selection of Sources of Evidence

The literature search carried out for this scoping review was done on PubMed using a combination of the keywords Artificial Intelligence (AI), COVID-19, Machine Learning (ML), and Low Middle-Income Countries (LMIC). After removing duplicates, a total of 35 articles were identified. These 35 articles were screened, and 13 articles were excluded which did not meet our inclusion criteria as they were not about either AI, or ML, or COVID-19. Full-text review of the remaining 22 articles was done and 9 were excluded because they either were not under the scope of our study or not mentioning specific AI applications in use. The remaining 13 articles were considered for the final review. All articles that were reviewed were in the English language. (Figure 2)

Characteristics and Results of Sources of Evidence

Characteristics of the selected articles are presented in Table 1, while aims/purposes and highlights/key results are presented in Table 2.

Results

Four Themes Were Identified From the Selected Articles

1. COVID-19 pandemic and the need of AI (See Figure 3)
2. The utility of AI in COVID-19 screening, contact tracing, and diagnosis

Table 1. Characteristics of Included COVID-19 Articles.

Author	Year	Study design	Data sources for AI development or evaluation	Category of AI	Included interventions	Funding/conflict of interest	Country
Li et al[15]	2020	Retrospective, multi-center study	Six centers	Deep learning technology (3D deep learning framework)	CT scan	-	China
Ting et al[16]	2020	Comment	-	Deep learning	-	Two authors hold a patent on a deep learning system for the detection of retinal diseases	Singapore
Vaishya et al[17]	2020	Rapid Review	-	-	-	-	India
Santosh[7]	2020	Review	-	Machine Learning (ML) algorithms	-	-	USA
Shi et al[18]	2020	Review	Several publicly available datasets	Deep learning methods	CT Scan and X-rays	Supported in part by Shanghai Science and Technology Foundation, National Key Research and Development Program of China, and Natural Science Foundation of Jiangsu Province	China
Mashamba-Thompson et al[19]	2020	Editorial	-	-	Mobile health intervention	-	South Africa
Allam et al[20]	2020	Perspective Paper	-	-	-	-	Mauritius

(continued)

Table 1. (continued)

Author	Year	Study design	Data sources for AI development or evaluation	Category of AI	Included interventions	Funding/conflict of interest	Country
Rao et al[21]	2020	Commentary	Mobile phone-based—online survey (PROPOSED)	-	Self-reported symptoms and basic travel history	-	Georgia
Yang et al[10]	2020	Original article	Epidemiological data on COVID-19 by the National Health Commission of China	Machine-learning artificial intelligence (AI) approach	-	Three authors serve as unpaid Editor-in-Chief, unpaid Executive Editor-in-Chief, and unpaid Editorial Board Member (Thoracic Surgery) of Journal of Thoracic Disease, respectively	China
Husnayain et al[22]	2020	Short Communication	Google Trends (GT)	Not specified	-	Funded in part by the Ministry of Science and Technology (MOST) and Ministry of Education (MOE) in Taiwan. The sponsor had no role in the research design or contents of the manuscript for publication.	Taiwan
Ayyoubzadeh et al[23]	2020	Original Paper	Google Trends (GT)	Deep Learning	-	-	Iran
Alimadadi et al[24]	2020	Editorial	-	Machine learning	-	Funding acknowledged by authors: X. Cheng (University of Toledo College of Medicine and Life Sciences, and NIDA Centre of Excellence) B. Joe (National Heart Lung and Blood Institute)	USA
McCall[25]	2020		-	Not specified	CT scan	-	USA

Table 2. Study Aims, Purposes, Highlights, and Key Results of the Included Studies.

Author	Title	Purposes/aim	Highlights/key results
Li et al[15]	Artificial Intelligence Distinguishes COVID-19 from Community-Acquired Pneumonia on Chest CT	To develop a fully automatic framework to detect COVID-19 using chest CT and evaluate its performances	Deep learning detects COVID-19 and uses chest CT to differentiate between lung infection (Pneumonia) and other lung pathologies
Ting et al[16]	Digital technology and COVID-19	To explore the potential application of 4 inter-related digital technologies (the IoT, big-data analytics, AI, and blockchain) to augmenting 2 traditional public-health strategies for tackling COVID-19: monitoring, surveillance, detection, and prevention of COVID-19; and mitigation of the impact to healthcare indirectly related to COVID-19	A broad range of digital technology is available to augment and enhance public-health strategies for COVID -19 detection, diagnosis, and its healthcare impact. The Use of digital technology for managing this global COVID-19 pandemic, a threat to public health, will influence stakeholders (governmental bodies and public) and hence may potentiate future use of such technologies in areas of healthcare other than Infectious diseases like many non-communicable and chronic diseases.
Vaishya et al[17]	Artificial Intelligence (AI) applications for COVID-19 pandemic	To review the role of AI as a decisive technology to analyze, prepare us for prevention, and fight with COVID-19 and other pandemics.	AI may have an instrumental and crucial role in formulating and developing the COVID-19 vaccine AI-based technology can be used for proper detection, analysis, tracing, and tracking of COVID-19 patients, and can predict the disease a-priori among those who may become infected in future
Santosh[7]	AI-Driven Tools for Coronavirus Outbreak: Need for Active Learning and Cross-Population Train/Test Models on Multitudinal/Multimodal Data	Unlike other healthcare issues, for COVID-19, to detect COVID-19, AI-driven tools are expected to have active learning-based cross-population train/test models that employ multitudinal and multimodal data, which is the primary purpose of the paper.	Implementing AI-driven tools at the start of the collection of data enables AI-based models to learn actively and simultaneously in the presence of field experts To gain higher confidence during the decision-making process, multiple l data types can be implemented at a time rather than relying just on 1 data type
Shi et al[18]	Review of Artificial Intelligence Techniques in Imaging Data Acquisition, Segmentation, and Diagnosis for COVID-19	This review aims to extensively discuss the role of medical imaging, especially empowered by AI, in fighting the COVID-19, which will inspire future practical applications and methodological research.	Reliable and efficient imaging solutions are provided by AI for COVID-19 AI-empowered imaging applications for COVID-19 have been reviewed in detail and their effectiveness is portrayed by 2 imaging modalities, that is, X-ray and CT.
Mashamba-Thompson et al[19]	Blockchain and Artificial Intelligence Technology for Novel Coronavirus Disease 2019 Self-Testing	A low-cost blockchain and artificial intelligence-coupled self-testing and tracking systems for COVID-19 and other emerging infectious diseases is recommended.	In low resource settings, with poor access to laboratory infrastructure, prompt deployment, and appropriate implementation of a low-cost Blockchain and AI-driven self-testing and tracking systems for COVID-19 can potentially help curb the transmissions of COVID-19, hence lowering the rates of related mortalities.

(continued)

Table 2. (continued)

Author	Title	Purposes/aim	Highlights/key results
Allam et al[20]	On the Coronavirus (COVID-19) Outbreak and the Smart City Network: Universal Data Sharing Standards Coupled with Artificial Intelligence (AI) to Benefit Urban Health Monitoring and Management	This perspective paper surveys the virus outbreak from an urban standpoint and advances how smart city networks should work towards enhancing standardization protocols for increased data sharing in the event of outbreaks or disasters, leading to better global understanding and management of the same	This paper highlights the urgent need to work towards the standardization of protocols for enhanced smart city communication and the need to democratize the smart city technology sphere to encourage equity and transparency amongst stakeholders, thereby providing more possible cooperation in the case of disasters.
Rao et al[21]	Identification of COVID-19 can be quicker through artificial intelligence framework using a mobile phone-based survey when cities and towns are under quarantine	The study proposes the use of a machine-learning algorithm to improve possible COVID-19 case identification more quickly using a mobile phone-based web survey	AI and deep learning-driven applications if, used promptly, can prove to not only be cost-effective but also be useful in assisting with diagnoses, treatment, decision making, and controlling COVID-19 in populations under quarantine.
Yang et al[10]	Modified SEIR and AI prediction of the trend of the epidemic of COVID-19 in China under public health interventions	A modified Susceptible Exposed-Infected-Removed (SEIR) epidemiological model that incorporates the domestic migration data before and after January 23 and the most recent COVID-19 epidemiological data to predict the epidemic progression	The Susceptible Exposed-Infected-Recovered (SEIR) model is effective in predicting the COVID-19 epidemic size and peaks The AI-based model trained on past SARS dataset shows promising results for predicting future epidemics
Husnayain et al[22]	Applications of Google Search Trends for risk communication in infectious disease management: A case study of the COVID-19 outbreak in Taiwan	This study explored the potential use of Google Trends (GT) for monitoring public restlessness toward COVID-19 infections in Taiwan	In response to the ongoing pandemic, Google Trends (GT) showed the potential to define the proper timing and location to imply appropriate risk communication strategies for affected populations.
Ayyoubzadeh et al[23]	Predicting COVID-19 Incidence Through Analysis of Google Trends Data in Iran: Data Mining and Deep Learning Pilot Study	This study aimed to predict the incidence of COVID-19 in Iran	Outbreak trends can be predicted via data mining algorithms, that can aid policymakers and health care managers in appropriate planning and allocation of healthcare resources.
Alimadadi et al[24]	Artificial intelligence and machine learning to fight COVID-19	N.A.	For artificial intelligence and machine learning research to develop strategies for COVID-19 prediction, diagnosis, and treatment, and for similar pandemics, in the future, a centralized collection of worldwide COVID-19 patient data will be beneficial.
McCall[25]	COVID-19 and artificial intelligence: protecting health-care workers and curbing the spread		AI can be used to predict future COVID 19 outbreaks and the effect of seasonality on these outbreaks. AI is designed to rapidly detect and differentiate between lesions of possible coronavirus pneumonia from other respiratory infections, on images, and their changing lung patterns to provide a quantitative report to assist doctors in quick decision making with accuracy. AI applications reduce the burden on clinicians by aiding in the diagnoses and monitoring of COVID-19

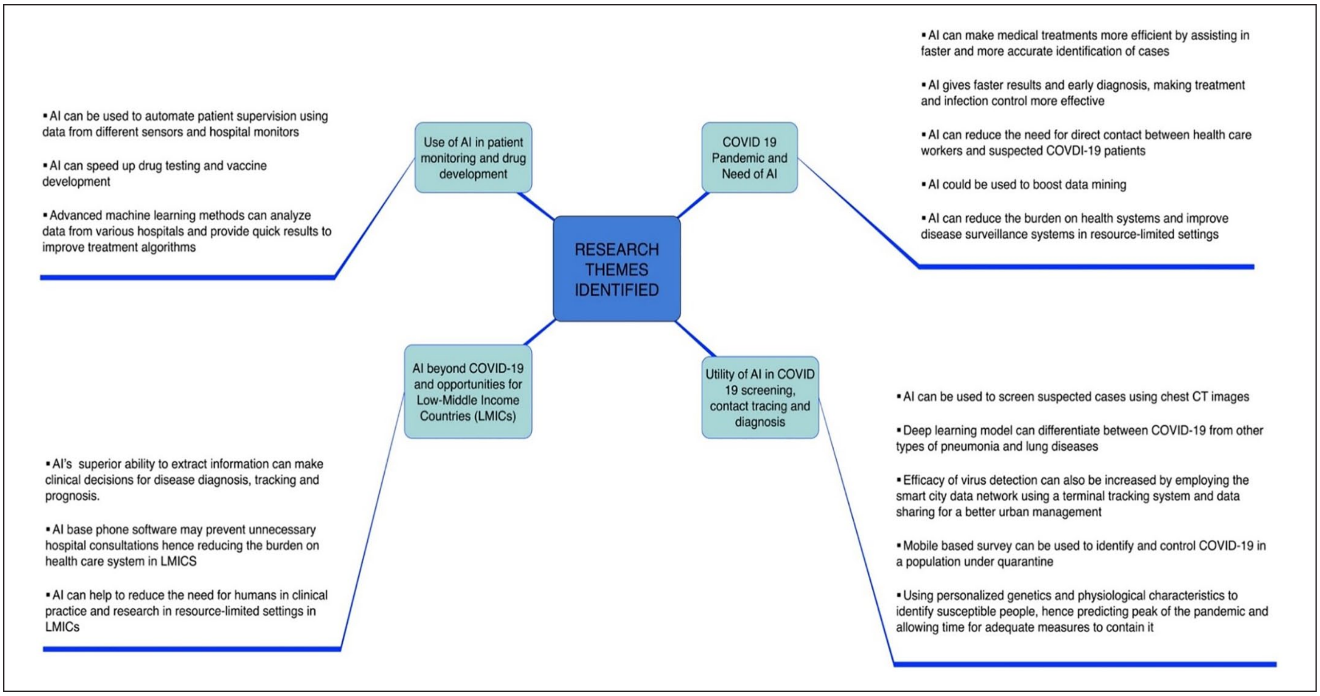

Figure 3. Synthesis of evidence.

3. Use of AI in COVID-19 patient monitoring and drug development
4. AI beyond COVID-19 and opportunities for Low-Middle Income Countries (LMIC)

COVID-19 Pandemic and the Need for AI

For a rapidly spreading pandemic like COVID-19, AI can make medical treatments more efficient in several ways. It can assist to increase the speed and accuracy of identification of cases.[18,21,24] For instance, the average processing time for a trained deep learning algorithm to identify COVID-19 on CT chest was 4.51 seconds, as compared to an average of 10 minutes 9 seconds required by a radiologist.[15,26] This means that if an AI algorithm is trained to have equal accuracy as a radiologist, it will report results about 135 times faster than a radiologist and can work round the clock without risking errors from fatigue. Extensive training and experience required by a radiologist to differentiate CT chest for COVID-19 patients, which may be very similar to CT chest in other types of pneumonia, will also be significantly longer as compared to "training" required by AI.[18] Since the identification of disease is critical for treatment and infection control in a pandemic, faster AI will produce much more desirable results than slower humans.[15,17]

Another potential application of AI is to position patients for radiological imaging. Healthcare workers can accurately position patients using cameras, speakers, and AI-assistance to ensure adequate position from a control room, without requiring direct contact with potential patients and risking the infection.[24,18]

To understand the COVID-19 outbreak, data mining methods could be utilized for exploratory and traditional analysis to deal with the health crisis efficiently.[23] Delivery of accurate and cost-effective tests for COVID-19 diagnosis is a challenge, that can be overcome by the use of AI technology to reduce the burden on health systems in resource-limited settings especially in LMIC.[16,19] Conventional AI-tools does not provide optimal results if less data is available so cross-population train/test-based AI-based models are required which can detect viruses in one country with the help of a model trained in another country to make automated detection of COVID-19, which will help in the containment of the virus.[7] The deep-learning prediction models and the resultant risk stratification may come in handy in formulating clinical judgment in a time-critical and resource-limited settings.[27]

The Utility of AI in COVID-19 Screening, Contact Tracing, and Diagnosis

Chest CT is deployed as a rapid and reliable technique for COVID-19 screening.[15] Suspected cases and high-risk groups can be screened and identified by using AI- algorithms (eg, with a travel or exposure history).[16,17,21] These patients can be divided according to disease severity, thus the high-risk groups can be isolated and diagnosis can be confirmed using laboratory-based PCR tests.[7,16] The spread of the virus could be tracked, and the most worst-hit areas can be timely identified.[17] This will help in time-effective controlling, monitoring, and prevention of the pandemic.[16,17] Since COVID-19 presents with similar features as other types of lung infections and pathologies, a deep learning model can accurately detect COVID-19 as distinct from other types of respiratory diseases with a sensitivity of 90% and specificity of 96% respectively.[15,25] AI-driven tools can detect tiny features in radiology data (pixel-level nodules) and AI-empowered image segmentation can perform accurate and efficient diagnosis and analysis, which may not be picked up by radiologists.[7,18]

Efficacy for virus detection can also be increased by employing the smart city data network using a terminal tracking system and data sharing for better urban management and the location of the next outbreak could be predicted.[20,25] Using a mobile-based survey, COVID-19 can be identified and controlled in the population under quarantine.[21] Susceptible people can also be identified based on personalized genetics and physiological characteristics.[24] A study used a modified Susceptible-Exposed-Infected-Recovered (SEIR) epidemiological model to effectively determine the COVID-19 peaks and the results were also analyzed through the Long Short-Term Memory (LSTM) model (Artificial Neural Network)). The model was trained on the data from the SARS epidemic and incorporation of COVID-19 epidemiological characteristics, such as the odds of transmission and incubation, it predicted the peak for new infections on February 4th in China. When the LTSM-predicted curve was compared with the actual number of new confirmed cases between January 22 and February 10, there was a remarkable fit between the both.[10] AI-based prediction models and internet sources could also be utilized for pandemic forecasting.[22,23] This suggests that the peak for the pandemic can be predicted, and as Peter Hotez (Baylor College of Medicine, Houston, TX, USA) stated, AI could also predict the effect of seasonality on the COVID-19 outbreak, so adequate measures can be taken timely for its containment and spread.[25]

Use of AI in COVID-19 patient monitoring and drug development

AI could be adopted as a tool for patient management. Online medical chatbots could help patients in recognition of their symptoms and guide the population on hand hygiene.[16] It can predict the risk of mortality by investigating the previous data of patients and can monitor the day to day updates of the patient by acquiring data through visual sensors like Red, Green, Blue (RGB), time of flight (TOF), pressure imaging, or thermal (FIR) cameras so that patient supervision is automated.[17,18]

AI can facilitate the discovery of drugs for treatment against COVID-19 by speeding up drug testing which is not possible by human labor.[16,17] Utilizing AI methods, Benevolent AI and Imperial College London have recently reported that a drug used for treatment of rheumatoid arthritis "Baricitinib," can be used effectively against the virus, while Insilico Medicine based in Hong Kong also published that they were able to design 6 new molecules that could stop viral replication utilizing AI algorithms.[25] Alpha Fold, (a deep learning system) created by Google DeepMind, provided valuable information about protein structures related with COVID-19 which could be utilized for vaccine formulation, which could have taken significantly longer by traditional experimental approaches.[24] Advanced machine learning technology is required to analyze vast amounts of treatment data for COVID-19, all around the world and it could be shared among hospitals using AI-tools for better treatment of patients globally.[24]

AI beyond COVID-19 and opportunities for Low-Middle Income Countries (LMIC). Moritz Kraemer, a spatial epidemiologist (University of Oxford, Oxford, UK) stated that "AI is relevant to this outbreak and in the future, it will become even more so."[25] AI technology has been successful in diagnosing COVID-19 through CT scans. This ability to extract information from chest CT has made deep learning an efficient tool in the field of radiology for making clinical decisions that is, for disease diagnosis, tracking, and prognosis.[15,18] Unnecessary hospital visits could be avoided by using Phone-based AI software that can assist in the detection and recording of data from patients (eg, daily temperature and symptoms) which will reduce the burden on clinicians and health care systems in LMIC.[16,25,28] There is a paucity of financial, material, and human resources in LMIC, AI can not only minimize the workload on human labor but it will also help in analyzing vast medical data and assist in decision making for patient treatment.[7,17] Apart from data collection, AI can also assist in biomedical researches, pharmaceutical chain management, and remote patient monitoring which will help improve health care in LMIC and play a pivotal role in predictive and preventive health care.[17,19] The health care systems could be effectively transformed by utilizing AI-based tools which will allow for data sharing and analysis and better urban health management.[20] This can also assist policymakers and healthcare-related managers in planning health care resources accordingly, as AI-based models hold the potential to predict future epidemics and can help to predict outcomes, understanding the trends in healthcare and model risk associations accordingly.[10,16,22,23]

Strengths and Limitations

Our study is based on current evidence on AI and ML use in COVID-19 pandemic and we have specifically highlighted LMIC aspects to our review which is a need of time. We have used rigorous and authentic methodology for reporting our review that is, PRISMA-ScR.

The Limitations of our scoping review are associated with databases that we included for our literature synthesis, we searched for the most popular literature indexing database "PubMed" as the topic is associated with Information technology, bio-informatics, and latest scientific developments that have a limited publication coverage. We may have missed some grey literature, and we focused our search on scientific and clinical related aspects of COVID-19 because our scope was to limit our search to the use of AI in medical technology specifically in the COVID-19 pandemic and LMIC perspective to it.

However, we have observed that with the emerging use of AI we can further aim for broader scoping reviews in the future.

Conclusion

AI has not only reduced the burden on health care systems by cost-effective and faster detection of COVID-19, screening, and diagnosis but it has also helped predict the location of the outbreak and future prediction of such outbreaks to allow sufficient preparedness at healthcare levels, this may aid the LMIC to prepare and allocate their healthcare resources in advance to avoid the collapse of healthcare systems. Hence it could be utilized as an effective tool by LMIC to ease the burden on their health care systems in several ways like planning, mitigation, diagnosis, and treatment of patients. The future of healthcare lies in AI-based tools and further utilities need to be explored in the coming times.

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