Applications of Artificial Intelligence (AI) for COVID-19 Pandemic

Ziwei Wang[1,*]

[1]*Community College of Philadelphia, Pennsylvania, United State, 19130*
**Corresponding author. Email: zwang16@student.ccp.edu*

ABSTRACT
The COVID-19 has caused a global pandemic. Until now, it has had a dramatic impact on society worldwide. COVID-19 has presented numerous challenges to the medical area. Unlike traditional approaches restraining the spread of the pandemic, artificial intelligence (AI) assists in the COVID-19 crisis in modern society. Artificial intelligence (AI) has many applications in health care, including detection and diagnosis, tracking and predicting treatment, and drug development. Motivated by the progress of artificial intelligence (AI) in the COVID-19 pandemic, this paper aims to provide clinicians and other readers with the current circumstance of the applications of AI in the COVID-19 pandemic. This paper provides evidence that AI contributes to improving the efficiency for diagnosis, particularly in graph-related areas, such as X-ray and CT scans. AI also analyses blood sample data and provides corresponding test results. This paper shows that the application of AI offers practical and powerful methods for outbreak tracking. It is expected that this paper enables researchers to better understand AI's applications for combating COVID-19 and encourages further studies reducing the worldwide pandemic.

Keywords: *Artificial Intelligence(AI), diagnosis, forecasting, drug development, machining learning, deep learning*

1. INTRODUCTION

COVID-19, caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), affects the world significantly, including the medical field, education, transportation, and politics. As the writing of this paper, the COVID-19 virus has spread worldwide. The current record of confirmed cases of COVID-19 is 250,610,452, with death nearly 5,064,585 [1]. Facing such a global crisis, people from all walks of life commit themselves to mitigate the substantial impact of the pandemic. Despite the spread of worldwide vaccination, the pandemic still threatens human livelihood [2]. In this baffling battle, new technology, artificial intelligence (AI), has played a positive and significant role.

The extensive application for artificial intelligence (AI) has been on the rise for a few years, peaking in 2018 [3]. This phenomenon relates to the advancement of AI and its applications in real life [4]. In the early days of the outbreak, China took advantage of artificial intelligence (AI): used facial recognition cameras to track infected patients' travel histories, sent robots for food and medicine delivery, and applied drones to disinfect public places [5].

In addition, many researchers are using AI to detect infectious patients through X-rays and CT scans [6]. During the COVID-19 pandemic, it is imperative to speedily design and develop effective drugs and vaccines to contain further mortality. In this sense, the application of AI in therapies can be a robust approach to identify ideal treatments [3].

The medical field has generated extensive data on diagnoses, patient histories and treatments [7]. When such a tremendous amount of information comes across the limitation of data processing, the accuracy of specific medical reports can impose a negative effect on healthcare-related decisions. However, by taking advantage of artificial intelligence and combing the processing results with professionals, the problem of inaccurate information can be primarily addressed. Patient information can be collected and analyzed more accurately.

To help mitigate the adverse effects of this pandemic, this paper reviews the application of AI in the early

detection and diagnosis of infected patients, mainly focusing on X-ray, CT Scan, and blood sample analysis. Moreover, it gives a thorough review for applying ML(machine learning) and DL(deep learning) in tracking and predicting the pandemic outbreak. Besides, it also provides AI's assistance in drug and vaccine development involving ML and DL. Reviewed papers in this work are gathered from: IEEE Xplore, Wiley, Google scholar and by using a subsequent of strings ("AI" OR "artificial intelligence") AND ("COVID-19" OR "SARS-CoV-2"). We hope this review could provide general guidance for researchers to do further AI-based studies in disease detection, virus tracking, and drug design and develop an enhanced response to COVID-19 and rapid reduction against future outbursts.

2. DETECTION AND DIAGNOSIS

Given the tremendous number of asymptomatic infected patients, it is essential to develop effective detection and diagnosis techniques to combat the COVID-19. Traditionally, the detection of respiratory viruses is called the reverse transcription polymerase chain reaction (RT-PCR) detection technique [8]. Such techniques facilitate the diagnosis of COVID-19 effectively, but they could be a massive drain of limited resources, such as finance and time. The problem is severe, especially for countries running out of testing kits. Therefore, better approaches are expected to be found in order to expedite the process of COVID-19 detection and tracking effectively. Recent studies revealed that, based on X-ray and CT scans [9], the preliminary diagnosis of COVID-19 can collects and evaluates the performance of different deep learning architectures used to analyze chest X-rays and their corresponding promising accuracy. Besides, convolutional neural networks and deep transfer learning contribute to the COVID-19 detection process [10]. In a study, the selected convolutional network model reaches the accuracy of 100% for identifying 260 images [11]. Additionally, AI's success in diagnosing COVID-19 pneumonia on CXR images is also shown in [12]. In addition to the high accuracy of dealing with chest X-rays, deep learning algorithms also have the potential to aid in rapidly analyzing CT exams for potential patients during the COVID-19 pandemic [13-15]. The above methods demonstrate desirable efficiency for COVID-19 detection. However, both of these approaches demand close attention from professional clinical facilities and advanced equipment. In contrast, the author proposes a method that eliminates the hassle of human intendance, named AI4COVID-19 [16]. It contains medical experts' knowledge and employs smartphones to record cough signals. AI4COVID-19 can identify cough resulting from COVID-19 from other types of cough and make a preliminary diagnosis. The accuracy of this cough detection algorithm is up to 95.60%, which is so promising that it can be applied on a large scale.

AI can be a considerable advantage in analyzing large amounts of data rapidly. Therefore, it has played a significant role in combat COVID-19 [17].

Some asymptomatic patients or at early stages of the disease show normal radiological test results. In this sense, integrating chest CT scans with clinical symptoms, exposure history, and laboratory testing to accurately diagnose patients from ordinary people is of importance [18].

Aside from comparatively high-cost COVID-19 detection methods, approaches with an inexpensive and readily available test based on clinical blood sample data have been used to enhance the efficiency of the diagnosis process. In such a context, a classifier with high specificity and high negative predictive values has been developed [19]. In addition, an ensemble approach combining deep neural network and random forest models was adopted to forecast mortality [20]. Another study implements the genetic algorithm and ML classifier to predict the COVID-19 based on the blood test sample and has more efficient performance than other algorithms [21].

Table 1. Summary of the results of studies which used artificial intelligence for detecting and diagnosing COVID-19 [10, 11-13, 15-16, 19-21]

Data Type	Model or Technology	Data Size	Accuracy	Sensitivity and Specificity
X-ray	InceptionV3, ResNet50, ResNet101, ResNet152, Inception-ResNetV2	2800 Normal and 341 COVID-19	96.1%	-
	InceptionV3, ResNet50, ResNet101, ResNet152, Inception-ResNetV2	1493 Viral pneumonia and 341 COVID-19	99.5%	-
	InceptionV3, ResNet50, ResNet101, ResNet152, Inception-ResNetV2	2772 Bacterial pneumonia and 341 COVID-19	99.7%	-
	convolutional network model: Inceptionv3	30 form COVID-19 and healthy	100%	-

	AI (Artificial Intelligence)	10 COVID-19, 10 pneumonia without COVID-19, 10 normal	97%	-
CT scans	Deep learning	150 normal and 120 suspected of COVID-19	-	94% Sensitivity and 98% specificity
	A 3D cross-layer sparse atrous convolution network	5608 COVID-19, 763 non-pneumonia, 756 mild community-acquired pneumonia	-	91.5% Sensitivity and 90.5% specificity
Blood sample	an artificial intelligence classification framework, ER-CoV	599 suspected of COVID-19	-	70.25% sensitivity and 85.98% specificity
	an artificial intelligence model: EDRnetdeep, neural network and random forest models	106 COVID-19	92%	100% sensitivity and 91% specificity
	the genetic algorithm and ML classifier	5,644 patients	98.7%	96.76% sensitivity and 98.80% specificity
Cough	Deep Transfer Learning-based Multi Class classifier (DTL-MC)	-	92.64%	-
	Classical Machine Learning-based Multi Class classifier (CML-MC)		88.76%	-
	Deep Transfer Learning-based Binary Class classifier (DTL-BC)		92.85%	-

3. FORECASTING AND TRACKING

To efficiently mitigate the harmful effects of the COVID-19 pandemic, insight into the near future under the pandemic aided by forecasting models is necessary. Several models of the COVID-19 pandemic model have been developed to analyze its transmission dynamics. Among these epidemic models, the susceptible, infected, and recovered (SIR) model is widely applied. However, it cannot be effectively applied in the COVID-19 pandemic because the recovered cases will not get infected again, and the model ignores two parameters [22]. In this sense, the development of efficient forecasting models is needed. Recently, several models have been developed to respond to such an urgent need. For example, a modified stacked auto-encoder that simulates the transmission dynamics of the COVID-19 was developed [18]. This AI-based method is based on the cumulative confirmed patients of COVID-19 across China from January 11 to February 27, 2020. The results turned out a high accuracy of the AI-based methods for Covid-19 forecasting.

In addition to modeling based on real-time cumulative infected people of COVID-19, some studies also take the social environment, climatic variables, pollution, and population density into their consideration. For example, a generalized additive model (GAM) was applied to explore the relationship between annual average temperature and infected people in Brazil [23]. A similar study was done in China [24]. In this study, in order to confirm the relationship between temperature and confirmed cases, locally weighted regression and smoothing scatterplot (LOESS), distributed lag nonlinear models (DLNMs), and random-effects meta-analysis were used. In the light of exogenous factors related studies, a study collects data of new cases and new deaths of COVID-19 from 166 countries [25]. It provides preliminary evidence that the increase in temperature and humidity may be partially suppressed the COVID-19 outbreak. These modeling results contribute to effective governance for healthcare policymakers and have instructive meanings for blocking transmission and preventing the further spread of COVID-19. Based on more studies regarding environmental factors, this study [26] overcomes one of the AI models' drawbacks that

need large datasets to construct the data pattern accurately. It introduces a unique set of AI models based on machine learning approaches concerning learning structures.

Machine learning methods typically use a sequence of data retrieved over a period of time to forecast the future of the COVID19 pandemic. The long short-term memory (LSTM) model has been frequently used. For example, multilayer perceptron (MLP) has been applied to predict the most significant number of affected, recovered, and dead people under the COVID-19 pandemic per place in each time unit [27]. Besides, LSTM with the Natural language processing (NLP) module has been used to update the infection frequency and enhance the model's predictive accuracy [28].

Deep learning is a well-known branch of machine learning. Regarding this direction, a novel model that predicts future 1-3 to 6 days' Covid-19 cases of 10 Brazilian states was proposed [29]. It predicts the Brazilian cumulative confirmed cases of COVID-19 using heterogeneous machine learning models and the stacking ensemble learning approach.

Table 2. Summary of the results of studies which used artificial intelligence for forecasting and tracking COVID-19 [18, 23-29]

Model or Technology	Factors to be Considered	Role
a modified stacked auto-encoder	cumulative confirmed patients of COVID-19	COVID-19 forecasting
a generalized additive model	annual average temperature and infected people	explore the relationship between annual average temperature and infected people in Brazil
locally weighted regression and smoothing scatterplot (LOESS), distributed lag nonlinear models (DLNMs)	temperature and confirmed cases	confirm the relationship between temperature and confirmed cases
A log-linear Generalized Additive Model(GAM)	new cases and new deaths of COVID-19, temperature and humidity	Find the relationship between temperature, humidity and confirmed cases of COVID-19
Bayesian regression neural network, cubist regression, k-nearest neighbors, quantile random forest, and support vector regression, variational mode decomposition (VMD)	Previous cumulative COVID-19 cases and daily temperature	COVID-19 forecasting
long short-term memory (LSTM) with multilayer perceptron (MLP)	infected, recovered, and deceased cases of COVID-19	predict the most significant number of affected, recovered, and dead people under the COVID-19 pandemic per place in each time unit
long short-term memory (LSTM) with the Natural language processing (NLP) module	the new confirmed cases on day t and the new confirmed cases on days t − 10 to t − 1the cumulative confirmed cases of COVID-19	update the infection frequency
heterogeneous machine learning models and the stacking ensemble learning	the cumulative confirmed cases of COVID-19	predicts future 1-3 to 6 days' Covid-19 cases

4. DRUG AND VACCINE DEVELOPMENT

Artificial intelligence has been used to develop drugs and vaccines with the help of super computers [30]. Over the past decade, deep learning methods have been used to forecast molecular properties and create target molecules

[31]. In this sense, deep learning(DL) will further contribute to drug discovery under the context of artificial intelligence. The learning procedure in deep learning (DL) includes automatic feature extraction from raw data [32]. In addition, deep learning's feature extraction contributes to excellent performance compared to other computer-aided models [33].

In a study, a deep docking model was developed to quickly predict the docking scores for billions of compounds, and finish virtual molecules screening in a short time [34]. The structures of the identified compounds are open to the public, which contribute to the drug design for COVID-19.

Machine learning (ML) can study and generalize the patterns from current data and infer from unseen data. In the last decade, machine learning has provided efficient implementation approaches to discover effective viral therapies [35]. Models trained by the machine learning method can predict inhibitor candidates based on structures. A model can identify patterns in the provided data and the advantages of developing new drugs and vaccines. A data-driven model for drug repurposing integrating ML and statistical analysis methods successfully forecasts potential drugs combating a certain coronavirus [36].

To date, artificial intelligence has been widely applied in the virtual screening of repurposed drug candidates and new chemical entities in the COVID-19 pandemic [35]. "Repurposed" compounds, antivirals previously designed to overcome other diseases, have yielded promising outcomes against SARS-CoV-2 in the cell. The repurposed drugs inhibit the replication of COVID-19, contributing to effective treatment for early affected patience [37]. A molecular network identifying repurposable drug targets was built, and then 30 drugs for repurposing were identified by analyzing the genomic sequence of three major members of the coronavirus virus family [38]. Differently, a coalescent of network-based methodologies for repurposable drug combinations was developed [39].

In addition to the contribution of the pharmaceutical field, AI also imposes a positive influence on vaccine development. Developing vaccines is one of the most effective strategies to fight against COVIV-19, but the developed vaccines still have safety concerns and cannot provide complete protection [40]. AI can overcome the challenges regarding these efficacy and safety problems of different vaccine candidates [41]. AI brings scientists a deeper understanding of the protein associated with SARS-CoV-2 and seeks possible targets [35]. For example, a Vaxign-ML-based reverse vaccinology tool was developed to predict targets that could be used to develop a safe and effective COVID-19 vaccine [42]. In addition, Crossman et al. used Recurrent Neural Networks(RNN) in deep learning to recognize potential targets for vaccine development [43]. Researchers at MIT's computer science and AI lab utilized two ML-based programs OptiAX and EvalMax, to develop COVID-19 vaccines for cellular immunity [44]. The former program can identify and develop peptide vaccines. The latter program is able to search for specific HLA (Human Leukocyte Antigen) haplotype frequencies working with certain peptides by looking through genetic structures within a variety of ethnicities [45]. This study points out that some peptides contribute to a better immune response.

Table 3. Summary of the results of studies which used artificial intelligence for drugs and vaccines development of COVID-19 [35, 38, 42-44]

Field	Model or Technology	Role
drug	Machine learning-based models	The virtual screening of repurposed drug candidates
	The neighbor-joining method with the MEGA-X software, the maximum composite likelihood model and 1000 bootstraps	
vaccine	Machine learning-based models	Understand the protein associated with SARS-CoV-2 and seeks possible targets
	A Vaxign-ML-based reverse vaccinology tool	Develop a safe and effective COVID-19 vaccine
	Recurrent Neural Networks(RNN)	Recognize potential targets for vaccine development
	Two ML-based programs OptiAX and EvalMax	Develop COVID-19 vaccines

5. CONCLUSION

Since the COVID-19 pandemic has dramatically affected the world, scientists and researchers have searched for effective methods that contain more negative impacts. Such approaches involve detection and diagnosis, tracing and forecasting, drug and vaccine development. In this case, Artificial Intelligence is proved to be promising to provide efficient help in the

healthcare sector. This paper provided evidence that AI dramatically improves the efficiency for diagnosis, especially in graph managing areas, such as X-ray and CT scans. AI is also economical and effective in analyzing blood sample data and provides corresponding detection results. This paper also discusses various AI-based models in forecasting the future pandemic. This review shows that the application of AI offers practical and powerful methods for outbreak tracking. The majority of the paper that involves drug development employed deep learning and machine learning algorithms, which proved to be advantageous for designing effective drugs for the pandemic. This paper also points out that AI has significant advantages in solving efficacy-and-safety-related problems of different vaccine candidates, predicting the promising application of AI in vaccine development. Nonetheless, we cannot employ AI without careful consideration and instructions from experienced clinicians and medical scientists. More effects have to be paid to increase the speed of eliminating future pandemics.

This paper only provides a limited amount of AI-based models and algorithms for drug and vaccine development in the pandemic. However, such information could help the general understanding of AI's application in healthcare, thereby improving the current situation. For future study, a simulation for the next wave of the pandemic outbreak is suggested to develop efficient surveillance strategies. Also, as countries begin to relax social restrictions, research is needed to assess potential new outbreak locations.

AUTHORS' CONTRIBUTIONS

This paper is independently completed by Ziwei Wang.

ACKNOWLEDGMENTS

I would like to thank my dissertation teacher for reviewing my paper and providing valuable suggestions.

REFERENCES

[1] Worldometer. COVID-19 CORONAVIRUS PANDEMIC, November 22, 2021. https://www.worldometers.info/coronavirus/

[2] Mikaela Gavas & Samuel Pleeck, Global Trends in 2021: How COVID-19 is Transforming International Development, MARCH 2, 2021 Retrieved from https://www.cgdev.org/publication/global-trends-2021-how-covid-transforming-international-development.

[3] Aman Chandra Kaushik & Utkarsh Raj, AI-driven drug discovery: A boon against COVID-19? [J] AI Open 1, 2020, pp.1–4.

[4] Travis B. Murdoch & Allan S. Detsky, The inevitable application of big data to health care. [J] Journal of American Medical Association, vol 309, No.13, 2019, pp. 1351-1352.

[5] Ruiz Estrada, Mario Arturo, The Uses of Drones in Case of Massive Epidemics Contagious Diseases Relief Humanitarian Aid: Wuhan-COVID-19 Crisis, February 29, 2020.

[6] Nguyen, Thanh, et al. Artificial Intelligence in the Battle against Coronavirus (COVID-19): A Survey and Future Research Directions, Apr 20, 2021.

[7] Ying Yang & Tao Chen, Analysis and Visualization Implementation of Medical Big Data Resource Sharing Mechanism Based on Deep Learning, in IEEE Access, vol. 7, pp. 156077-156088.

[8] Q. V. Pham, D. C. Nguyen, T. Huynh-The, W. J. Hwang and P. N. Pathirana, Artificial Intelligence (AI) and Big Data for Coronavirus (COVID-19) Pandemic: A Survey on the State-of-the-Arts, in IEEE Access, vol. 8, 2020, pp. 130820-130839.

[9] Muhammad Ilyas1& Hina Rehman & Amine Nait-ali Detection of Covid-19 From Chest X-ray Images Using Artificial Intelligence: An Early Review, Apr, 11, 2020.

[10] Ali Narin & Ceren Kaya & Ziynet Pamuk, Automatic detection of coronavirus disease (COVID-19) using X-ray images and deep convolutional neural networks, Pattern Analysis and Applications, 2021(24):1207–1220.

[11] Fatima M. Salman & Samy S. Abu-Naser & Eman Alajrami & Bassem S. Abu-Nasser & Belal A. M. Ashqar, COVID-19 Detection using Artificial Intelligence, International Journal of Academic Engineering Research (IJAER) Vol. 4, Issue 3, March, 2020, pp. 18-25.

[12] Borkowski, Andrew A et al. Using Artificial Intelligence for COVID-19 Chest X-ray Diagnosis, Federal practitioner: for the health care professionals of the VA, DoD, and PHS vol. 37, 9, 2020, pp.398-404.

[13] Ophir Gozes, Maayan Frid-Adar et al. Rapid AI Development Cycle for the Coronavirus (COVID-19) Pandemic: Initial Results for Automated Detection & Patient Monitoring using Deep Learning CT Image Analysis, March 12, 2021.

[14] Yao, Jin-Cao et al. AI detection of mild COVID-19 pneumonia from chest CT scans. European radiology vol. 31, 2021 (9): 7192-7201.

[15] Harmon, S.A., Sanford, T.H., Xu, S. et al. Artificial intelligence for the detection of COVID-19

pneumonia on chest CT using multinational datasets. Nat Commun 11, 4080, 2020.

[16] Ali Imran, Iryna Posokhova et al. AI4COVID-19: AI enabled preliminary diagnosis for COVID-19 from cough samples via an app [J] Informatics in Medicine Unlocked 20 , 2020, pp.100378.

[17] Mei, X., Lee, HC., Diao, Ky. et al. Artificial intelligence–enabled rapid diagnosis of patients with COVID-19. Nat Med 26, 2020, pp.1224–1228.

[18] Zixin Hu, Qiyang Ge, Shudi Li, Li Jin, Momiao Xiong. Artificial Intelligence Forecasting of Covid-19 in China. Mar 1, 2020. https://arxiv.org/abs/2002.07112

[19] Soares, F., Villavicencio, A., Fogliatto, F. S., Rigatto, M. H., Anzanello, M. J., Idiart, M. A., & Stevenson, M., A novel specific artificial intelligence-based method to identify COVID-19 cases using simple blood exams. medRxiv, 2020.

[20] Ko, Hoon et al, An Artificial Intelligence Model to Predict the Mortality of COVID-19 Patients at Hospital Admission Time Using Routine Blood Samples: Development and Validation of an Ensemble Model, Journal of medical Internet research vol. 22, 12 e25442. 23, Dec 2020.

[21] Doewes, R. I. & Nair, R. & Sharma, T., Diagnosis of COVID-19 through blood sample using ensemble genetic algorithms and machine learning classifier, World Journal of Engineering, 2021.

[22] Q. V. Pham, D. C. Nguyen, T. Huynh-The, W. J. Hwang and P. N. Pathirana, Artificial Intelligence (AI) and Big Data for Coronavirus (COVID-19) Pandemic: A Survey on the State-of-the-Arts, in IEEE Access, vol. 8, 2020, pp. 130820-130839.

[23] Prata, David N et al. Temperature significantly changes COVID-19 transmission in (sub) tropical cities of Brazil, The Science of the total environment vol. 729, 2020, pp.138862.

[24] Shi, Peng et al. Impact of temperature on the dynamics of the COVID-19 outbreak in China, The Science of the total environment vol. 728, 2020, pp.138890.

[25] Yu, Wu & Jing, Wenzhan & Liu, Jue & Ma, Qiuyue & Yuan, Jie & Wang, Yaping & Du, Min & Liu, Min. Effects of temperature and humidity on the daily new cases and new deaths of COVID-19 in 166 countries. Science of The Total Environment, 2020.

[26] Silva da, Ramon Gomes et al. Forecasting Brazilian and American COVID-19 cases based on artificial intelligence coupled with climatic exogenous variables. Chaos, solitons, and fractals vol. 139, 2020, pp.110027.

[27] Car, Zlatan & Baressi Šegota, Sandi & Anđelić, Nikola & Lorencin, Ivan & Mrzljak, Vedran. Modeling the Spread of COVID-19 Infection Using a Multilayer Perceptron. Computational and Mathematical Methods in Medicine, 2020.

[28] Zheng, Nanning et al. Predicting COVID-19 in China Using Hybrid AI Model. IEEE transactions on cybernetics vol. 50,7, 2020, pp. 2891-2904.

[29] Ribeiro, Matheus Henrique Dal Molin et al. Short-term forecasting COVID-19 cumulative confirmed cases: Perspectives for Brazil. Chaos, solitons, and fractals vol. 135, 2020, 109853.

[30] Joseph Bullock et al, Mapping the Landscape of Artificial Intelligence Applications against COVID-19, Journal of Artificial Intelligence Research 69 (2020) 807-845, Jan 11, 2021.

[31] Zhong, F., Xing, J., Li, X. et al. Artificial intelligence in drug design. Sci. China Life Sci. 61, 2018, pp.1191–1204.

[32] Yann LeCun, Yoshua Bengio & Geoffrey Hinton, Deep learning, 436, NATURE, VOL 521, May 28, 2015.

[33] Zhavoronkov, A., Ivanenkov, Y.A., Aliper, A. et al. Deep learning enables rapid identification of potent DDR1 kinase inhibitors. Nat Biotechnol 37, 2019, pp.1038–1040.

[34] Ton, Anh-Tien et al. Rapid Identification of Potential Inhibitors of SARS-CoV-2 Main Protease by Deep Docking of 1.3 Billion Compounds. Molecular informatics vol. 39, 8, 2020: e2000028.

[35] Keshavarzi Arshadi, Arash et al. Artificial Intelligence for COVID-19 Drug Discovery and Vaccine Development. Frontiers in artificial intelligence vol. 3, 65, Aug. 18, 2020.

[36] Ge Y, Tian T, Huang S, et al. A data-driven drug repositioning framework discovered a potential therapeutic agent targeting COVID-19, 2020.

[37] Simonis, Alexander et al. A comparative analysis of remdesivir and other repurposed antivirals against SARS-CoV-2. EMBO molecular medicine vol. 13,1 (2021): e13105.

[38] Li, Xu et al. Network bioinformatics analysis provides insight into drug repurposing for COVID-19. Medicine in drug discovery vol. 10 (2021): 100090.

[39] Zhou, Y., Hou, Y., Shen, J. et al. Network-based drug repurposing for novel coronavirus 2019-nCoV/SARS-CoV-2. Cell Discov 6, 2020.

[40] Rawat, Kajal et al. COVID-19 vaccine: A recent update in pipeline vaccines, their design and development strategies. European journal of pharmacology vol. 892 (2021): 173751.

[41]Arora G, Joshi J, Mandal RS, Shrivastava N, Virmani R, Sethi T. Artificial Intelligence in Surveillance, Diagnosis, Drug Discovery and Vaccine Development against COVID-19. Pathogens, 2021, 10(8):1048.

[42] Ong, E., Wong, M.U., Huffman, A., He, Y. COVID-19 coronavirus vaccine design using reverse vaccinology and machine learning. Front. Immunol, 2020.

[43] Crossman, Lisa, Leverging Deep Learning to Simulate Coronavirus Spike proteins has the potential to predict future Zoonotic sequences, 2020.

[44] Liu, Ge et al. Predicted Cellular Immunity Population Coverage Gaps for SARS-CoV-2 Subunit Vaccines and Their Augmentation by Compact Peptide Sets. Cell systems vol. 12, 1, 2021, pp.102-107.

[45] Liu, Ge et al. Computationally Optimized SARS-CoV-2 MHC Class I and II Vaccine Formulations Predicted to Target Human Haplotype Distributions. Cell systems vol. 11, 2, 2020, pp.131-144.