How Machine Learning and Artificial Intelligence Can Help Us Fight the Next Pandemic

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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STS Research Paper

Introduction

The COVID-19 pandemic will likely be remembered as the most impactful event of the early 21st century. Causing over 6 million deaths to date and harming the well-being of far more, the pandemic has done an immense amount of damage to the world (World Health Organization, 2023). If through some means the pandemic had been stopped in its tracks before it had truly begun, a great service would have been done for the world. Analysis of historical data has shown that the next pandemic will likely occur within this century, so we must be prepared for its arrival. Due to their ability to quickly process vast amounts of data, artificial intelligence (AI) and machine learning (ML) can help us turn the next pandemic into a week-long story instead of a years-long tragedy (SAS India, 2022). This paper will examine the following research question: How can humanity use AI and ML to prevent and minimize future pandemics? To answer this question, the STS (Science, Technology, and Society) frameworks of political technologies and risk analysis will be used as tools for further examination of this question.

Research question and methods

This paper examines the following research question: How can humanity use artificial intelligence (AI) and machine learning (ML) to prevent and minimize future pandemics? The research was performed by searching for academic papers using keywords and key terms such as “AI,” “Pandemic,” “COVID-19,” “Machine Learning,” “Disease X,” and other related terms. Additionally, terms such as “Risk Society” and “political technology” were used to explore the current state of STS discussion in this area. These terms were selected because they are highly relevant to the topic at hand. “Disease X” is a term coined by the World Health Organization to describe a currently unknown future deadly disease, and it has been adopted by many academics and officials in discussions of how we can prepare for pandemics (The Economist, 2018). This method of research is aligned very closely with the topic at hand, as many of the techniques in this area of research have not yet been implemented, and remain in the realm of theory and academic discussion.

Background on Disease and AI

Highly infectious diseases have been a fundamental part of human life since the very beginning of organized society. Due to the ways we interact with one another, pathogens can spread from person to person through physical contact and sometimes simply due to the presence of other people. When outbreaks of diseases get particularly intense and deadly, they can sometimes require extreme courses of action to protect the health of the public. These disease events have come to be known as pandemics (Piret & Boivin, 2021)

The COVID-19 pandemic, and the mistakes that were made in its infancy, will inform much of this analysis, as it is a prime example of how an infectious disease can spiral into a worldwide problem. The 2019 novel coronavirus, as it was called, began in Wuhan, China as an “atypical pneumonia”, and was able to spread beyond the Chinese border before anyone knew what was happening. The disease grew from a small localized event to a worldwide pandemic that was killing thousands of people every day in just under 3 months (CDC, 2022) Better recognition and swifter action likely could have prevented the spread of COVID-19, but the technological infrastructure and social awareness that would have been necessary was not in place. For future pandemics, we will likely be able to do a better job if we use technology to our advantage.

Artificial Intelligence (AI) is a field of study that uses computational power to analyze data and solve problems (IBM). In the same way that ChatGPT has created a method for having a realistic human conversation, and social media algorithms have nearly mastered the art of capturing human attention, AI can serve as a watchdog for potential pandemics. (OpenAI, 2023). Due to its ability to incorporate large amounts of data and recognize patterns, AI is a natural fit for the fight against pandemics. Within AI, there are several subfields such as natural language processing, neural networks, and machine learning. Machine learning (ML) is perhaps the most prominent form of AI in which algorithms are used to process data through the lens of parameters or weighting (Bzdok et al., 2017). For undocumented biological phenomena which do not have established models, such as the spread of a novel pandemic, machine learning can be a powerful tool for providing insight.

The STS View

Due to the large volume of data required and the vast implication of its use on the lives of the public, AI has long been considered a political technology. Within the STS field, there are a variety of perspectives on AI and politics. In their paper, "Opportunity for renewal or disruptive force? How artificial intelligence alters democratic politics", authors König and Wenzelburger argue that while AI could result in the poisoning of the information environment that allows democracy to function, it could also increase government accountability if it is used as a watchdog (König & Wenzelburger, 2020). Viewing the issue from a different lens, Blake Murdoch argues that applying AI to medical information raises significant concerns over patient privacy, and argues for improved methods of anonymization (Murdoch, 2021). While these and other authors have different perspectives on how AI can and will affect politics, they seem to agree that it will have *some* effect, which strengthens the idea that AI is a political technology.

Additionally, the risk analysis that will have to be performed once a pandemic has been identified must be considered. This type of decision-making is discussed at length in Beck's idea of the Risk Society, where he claims modern society has become increasingly focused on the management and analysis of risk (Mythen, 2004). Several STS authors have applied the idea of the risk society to the COVID-19 pandemic, and how this frame of mind can lead to interesting conclusions. Sweden's relaxed policies on COVID-19, which became the subject of worldwide scrutiny, are said to have been in line with Risk Society thinking (Nygren & Olofsson, 2020). Pietrocola et al. argue that as a result of the Risk Society style thinking becoming prevalent and the presence of the COVID-19 pandemic, there must be increased attention paid to scientific education so that the general public is informed enough to operate within the Risk Society (Pietrocola et al., 2020). Most authors on this subject seem to agree that a pandemic leads to increases in Risk Society thinking, which could have a variety of different effects.

Results and Discussion

Artificial Intelligence and Machine learning have been used in several ways to prevent and minimize the impact of pandemics. Many of these strategies were used during the COVID-19 pandemic, including the modeling of key statistics, assisting with diagnostics, developing effective vaccines, and tracking relevant individuals. Additionally, several strategies could be used to fight pandemics that remain largely unused or underdeveloped. Specifically, widescale wastewater tracking and modifying the capabilities of drug discovery algorithms are examined in this paper. Overall, this research suggests that preventing future pandemics will require both an expansion of existing technology and the implementation of future innovations.

The future of fighting pandemics can be seen by looking at how artificial intelligence and machine learning were used to fight the COVID-19 pandemic. Future applications of these methods would likely involve wider and more in-depth implementation of these technologies, which will be easier in the future as computational power and complexity increase.

Modeling Key Statistics

One of the main ways machine learning was used to help control the COVID-19 pandemic was through modeling data that is important for policy-making such as future case counts, suspected cases, deaths, and intervention effectiveness. One study published in the very early stages of the pandemic found a good way to predict possible infections in Wuhan by using a machine learning model. By manipulating a 14-day dataset of COVID infections and tuning different model parameters, the scientists found a model that had less error than traditional time series modeling methods, such as integrated moving averaging and exponential growth. This model took the form of a polynomial neural network, which is a commonly used form of machine learning (Fong et al., 2020). Another study, later in the pandemic, found that using the data from tweets from public Twitter accounts had the potential to produce predictions regarding case counts and outbreaks in certain areas. By analyzing the wording of tweets related to COVID-19 symptoms using Natural Language Processing (NLP), the researchers found that the number of tweets regarding symptoms was relatively predictive of later released government numbers of lab-confirmed COVID-19 cases (Golder et al., 2022). NLP is a form of machine learning that views language through a probabilistic lens and is capable of translation, summarization, and sentiment analysis, which was the technique used in the study in question (IBM). Another study, which took the form of a preprint (non-peer-reviewed study) released by a company called Kinsa, claims that data from smartphone-connected thermometers can predict the rise of official case counts of COVID-19. The data from these thermometers, which are a product of Kinsa, was inserted into a gaussian process model, which is one of the lesser-used forms of machine learning, to generate a series of predictions regarding future COVID-19 case counts. The authors claim that this method performed favorably when compared to Carnegie-

Mellon's Epicast and Stat models, but the research remains unpublished, perhaps due to conflicts of interest (Chamberlain et al., 2020).

Performing Diagnostics

In addition to the many ways AI and ML were useful in modeling the spread and impact of the pandemic on a societal level, they also served as valuable tools for the medical community to improve diagnostic capabilities. The RT-PCR test, which is commonly used to determine whether a patient's sample is COVID-19 positive or COVID-19 negative, may still produce false-negative results in cases where the viral load is low and the patient has mild or no symptoms (Mallet et al., 2020). As a result, incorporating various AI-based methods for screening and diagnosing COVID-19 has been beneficial in determining the disease status of patients. For example, one study found that a convolutional neural network (CNN) based model can be useful to identify COVID-19 infection in patients through the analysis of chest X-rays (Wang et al., 2020). This model analyzes X-ray images without the need to consult a radiologist, which has the potential to reduce costs and boost hospital time efficiency. Furthermore, machine learning was useful for improving diagnostics by analyzing blood tests for signs of COVID-19 (Brinati et al., 2020). Several examples of published models can be found that are able to classify whether a patient is COVID-19 positive based on hematological values such as hemoglobin content and blood cell counts (Arora et al., 2021). These models had accuracies of 90-95%, which is accurate enough to be useful, especially in cases where RT-PCR is likely to be unreliable or is simply not available. Moreover, a separate study found that when natural language processing is used to analyze text-based clinical reports of patients, disease status could be determined with an accuracy of over 96% (Khanday et al., 2020).

Aiding in Vaccine Development

Vaccine development was perhaps the most important way AI was used during the COVID-19 pandemic. The onset of the pandemic sent thousands of scientists and companies into a frenzy in search of a safe and effective vaccine that could prevent the spread of COVID-19. The ability of AI to quickly analyze millions of data points was part of the reason for the incredibly fast development of mRNA-based COVID vaccines, such as the Moderna and Pfizer vaccines. This process occurred much more quickly than the initially estimated timelines of development, which were based on previous large-scale vaccine efforts (McKinsey, 2021). According to Dave Johnson, who is the chief data and artificial intelligence officer at Moderna, the company developed proprietary algorithms to find an effective match between the desired amino acid sequence (the protein for which the vaccine is designed) and a nucleotide sequence (mRNA), since there is a vast amount of nucleotide sequences that can code for a given protein. In a 2021 interview, Johnson also mentioned how algorithms were also used to optimize a potential match that is found through the process just described. “We have algorithms that can take one [sequence] and then optimize it even further to make it better for production or to avoid things that we know are bad for this mRNA in production or for expression” he said, while later commenting about how scientists at Moderna can “just press a button and the work is done for them” (Ransbotham & Khodabandeh, 2021). Johnson’s comments are reflective of the transformative nature of AI, and how it can both simplify existing processes and open new possibilities for vaccine design and development. Whereas the mRNA vaccines developed by Pfizer and Modern primarily target the spike (or “S”) protein of SARS-CoV-2 (the virus that causes COVID-19), a 2020 study out of the University of Michigan found that there are several other candidate proteins related to the virus that could be used to develop an effective vaccine through the use of reverse vaccinology and machine learning (Ong et al. 2020). Reverse vaccinology is a technique in which vaccines are developed through bioinformatic data analysis of the pathogen in question, making it a primary use case for machine learning and other applications of AI.

Tracking Individuals and the politics of AI

Another way in which AI and ML were used during the COVID-19 pandemic was the tracking of individuals. AT the beginning of the pandemic, China and Russia capitalized on pre-existing facial recognition technology powered by AI and surveillance cameras to detect non-compliant individuals who failed to adhere to required self-isolation or quarantine protocols (Reuters, 2021; Yuan, 2020). This method of tracking people underscores the idea that AI is a political technology, whose wide-scale use is often going to be pitted against the data privacy concerns of citizens. In addition to using AI-powered surveillance to determine who was following quarantine, China's system became advanced enough to recognize both those who were wearing masks and those who weren't (Yang & Zhu, 2020). The progress and implementation of these systems should be a cause of concern for those who are generally concerned about the way technology can and will continue to affect political and social life. A system that can track the behavior of mass amounts of individuals is also a system that can categorize and scrutinize people, making political and societal control easier than ever for those with their hands at the control panel. Even on a smaller scale, employers used similar facial recognition systems to help employees scan into work in a contactless manner (Pascu, 2020). Similar to the way airport security became increasingly stringent after the September 11th attacks, we may have entered a new era concerning expectations of data privacy, in which the use of AI and other machine learning technologies will lead to questions over the role of the state.

While the progress made in the use of AI as a result of COVID-19 will certainly be important in terms of countering the next pandemic, it is also important to consider how AI and ML might be used to prevent future pandemics entirely. Furthermore, future AI advancements will provide us with enhanced capabilities in some of the areas already discussed, improving our pandemic-fighting abilities in ways we currently can only theorize about.

Detection of Threats

Perhaps the most intuitive method of preventing a pandemic is stopping the spread of a disease before it gets out of control. Due to the speed at which a potential threat must be recognized and the severity of potential interventions, this method of stopping a pandemic presents a challenging problem. In the future, however, AI might give us the capability of detecting potential pandemics before they spiral out of control. For example, an early version of what detection systems might look like in the future can be seen by looking at how diseases are sometimes able to be tracked through wastewater. For example, during the COVID-19 pandemic, the United Kingdom expanded the sampling of wastewater treatment facilities to better track COVID-19. Typically, in the disease progression of COVID-19, infected persons spread shed virus material in their feces within a few days of symptoms appearing, which can sometimes be before they would test positive on a typical RT-PCR nasal swab test (Baraniuk, 2020). This dynamic has also been seen with other diseases, such as Hepatitis A and norovirus, and is not unique to COVID-19. Disease material detected in wastewater, therefore, serves as an early warning signal that an outbreak may be about to occur. However, current sewage monitoring technologies are highly imperfect and often suffer from inaccuracies and slow data processing, which make them a perfect area for innovation through the implementation of advanced AI and ML (Su et al., 2021). A future system might involve integration with wastewater infrastructure itself such as piping, to increase the precision by which outbreaks can be detected. This system would allow for the identification and containment of a novel, deadly pathogen before it would be able to spread.

Monitoring Man-made Pathogens

When thinking about future pandemics and the risk they pose, it is important to recognize that there are several different ways in which these events could occur. A particularly frightening possibility would be a genetically engineered virus that combines the characteristics of a highly infectious disease with a highly deadly disease, two forces that tend to counteract one another as natural viruses spread and mutate. As synthetic biology becomes more accessible and drug-discovery algorithms increase their mastery of human biology, the risk of a bioweapon or a man-made pandemic being released will likely increase. An example that shows the dangers at play was seen at Spiez CONVERGENCE, which is a biennial conference where trends in biological and chemical research are discussed through the framing of national security. There, a company called Collaborations Pharmaceuticals demonstrated how they accidentally discovered that their proprietary drug discovery AI was able to easily produce pathways to development for both known chemical weapons and many entirely new toxic compounds (Sohn, 2022). As a result, this is an area in which AI systems must police themselves, and the developers of these systems must do their best to include checks and controls on what types of information they release to the user. A future solution to this problem might involve a separate algorithm, which will likely have to be agreed upon by world governments, which conducts simulations of what might happen if a given substance was produced and placed in a human body. If successful, this algorithm would likely have to be legally required in the development of drug discovery AI systems, and would hopefully stop malicious actors.

Interventions and Risk Analysis

If a novel, deadly pathogen with the potential to spread is discovered by AI in the early stages of transmission, hard problems are immediately presented. That occurrence, which will have been an absolute triumph of human ingenuity and foresight, is merely the beginning of the story. It is then up to governments to figure out how to handle the situation. To come up with a solution, governments must perform a risk analysis, in that they will be forced to decide while balancing tradeoffs in an uncertain scenario. The key variable in making decisions regarding societal risk when it comes to a deadly disease is the intensity of the sickness and the likelihood of spread. When attempting to operate ethically, the justification for extreme measures is extreme circumstances. For example, if a very deadly, highly contagious disease is discovered through wastewater to be localized to a single geographic area, it becomes increasingly difficult to rationalize non-intervention. In this scenario, the most ethical action for all parties (inside and outside of the area) might be similar to China's Zero-Covid policy, in which the government sometimes forcibly trapped people in their homes to stop the spread (AP, 2022). In another scenario, where a novel, highly infectious disease is identified but poses less risk than the common cold, it is likely not justifiable to enact strict lockdown measures that will negatively affect the livelihood of people within the area in question. These problems are difficult to solve, and they require careful thought and justification in order for sound decisions to be made. A world in which governments are increasing involved in determining appropriate levels of collective risk is one that will be strongly showing the concept of the Risk Society, as outlined by Beck (Mythen, 2004).

Limitations and Future Work

This research is limited in its scope due to both its methods and the context in which it was performed. The addition of keywords to the search criteria could have provided new information regarding topics that were not mentioned. Furthermore, a larger team performing research together could have yielded more insight into the topics discussed as well as those that were not mentioned. Future work in this area should expand the breadth of the topics covered, as well as explore different methods of acquiring information, such as performing interviews, surveys, or focus groups.

Conclusion

In the fight against future pandemics, we would do well to heed the lessons we learned from COVID-19, and the advances we made as a result of its challenges. Future pandemics will likely involve similar dynamics in terms of social distancing policies, rushed vaccine timelines, a need for accurate diagnostics, and modeling of key statistics such as case counts and deaths. By making the necessary investments to innovate in these areas using the capabilities provided to us by AI and ML, we can be better prepared for the next pandemic and be more able to reduce its societal impact. Additionally, advances in AI are likely to bring us new capabilities that have yet to be implemented, such as widespread and regular wastewater sampling and guardrails to prevent man-made pandemics, that will help us save lives by preventing deadly pathogens from wreaking havoc across the world. While they will be helpful, each of these efforts will come with its own set of obstacles, given the inherently political nature of advanced AI monitoring systems and the risk analysis that must be performed before enacting any intervention.

References

Arora, G., Joshi, J., Mandal, R. S., Shrivastava, N., Virmani, R., & Sethi, T. (2021). Artificial Intelligence in Surveillance, Diagnosis, Drug Discovery and Vaccine Development against COVID-19. *Pathogens*, *10*(8). https://doi.org/10.3390/pathogens10081048

Associated Press. (2022, December 8). *Explainer: China's relaxed 'zero-covid' brings big changes*. apnews.com. Retrieved March 22, 2023, from https://apnews.com/article/health-china-covid-government-and-politics-fb77c852a1ab66b0827863c26939cc0f

Baraniuk, C. (2020). Sewage monitoring is the UK's next defence against covid-19. *BMJ*, *370*. https://doi.org/10.1136/bmj.m2599

Brinati, D., Campagner, A., Ferrari, D., Locatelli, M., Banfi, G., & Cabitza, F. (2020). Detection of COVID-19 Infection from Routine Blood Exams with Machine Learning: A Feasibility Study. *Journal of Medical Systems*, *44*(8), 135. https://doi.org/10.1007/s10916-020-01597-4

Bzdok, D., Krzywinski, M., & Altman, N. (2017). Points of Significance: Machine learning: a primer. Nature methods, 14(12), 1119–1120. https://doi.org/10.1038/nmeth.4526

CDC Museum Covid-19 Timeline. Centers for Disease Control and Prevention. (2022, August 16). Retrieved February 5, 2023, from https://www.cdc.gov/museum/timeline/covid19.html

Chamberlain, S. D., Singh, I., Ariza, C., Daitch, A., Philips, P., & Dalziel, B. D. (2020). Real-time detection of COVID-19 epicenters within the United States using a network of smart thermometers. *MedRxiv*. https://doi.org/10.1101/2020.04.06.20039909

The Economist. (2018, March 23). *What is disease X?* economist.com. Retrieved March 22, 2023, from https://www.economist.com/the-economist-explains/2018/03/23/what-is-disease-x

Fong, S. J., Li, G., Dey, N., Crespo, R. G., & Herrera-Viedma, E. (2020). Finding an Accurate Early Forecasting Model from Small Dataset: A Case of 2019-nCoV Novel Coronavirus Outbreak. *International Journal of Interactive Multimedia and Artificial Intelligence*, *6*(1), 132+. https://link.gale.com/apps/doc/A618575521/AONE?u=anon~b898fcc3&sid=googleScholar&xid=f2e16d52

What is Artificial Intelligence (AI)? IBM. (n.d.). Retrieved February 5, 2023, from https://www.ibm.com/topics/artificial-intelligence

What is natural language processing? IBM. (n.d.). Retrieved March 22, 2023, from https://www.ibm.com/topics/natural-language-processing#:~:text=the%20next%20step-,What%20is%20natural%20language%20processing%3F,same%20way%20human%20beings%20can.

Khanday, A. M. U. D., Rabani, S. T., Khan, Q. R., Rouf, N., & Mohi Ud Din, M. (2020). Machine learning based approaches for detecting COVID-19 using clinical text data.

International Journal of Information Technology, *12*(3), 731–739. https://doi.org/10.1007/s41870-020-00495-9

König, P. D., & Wenzelburger, G. (2020). Opportunity for renewal or disruptive force? How artificial intelligence alters democratic politics. *Government Information Quarterly*, *37*(3), 101489. https://doi.org/10.1016/j.giq.2020.101489

Mallett, S., Allen, A. J., Graziadio, S., Taylor, S. A., Sakai, N. S., Green, K., Suklan, J., Hyde, C., Shinkins, B., Zhelev, Z., Peters, J., Turner, P. J., Roberts, N. W., di Ruffano, L. F., Wolff, R., Whiting, P., Winter, A., Bhatnagar, G., Nicholson, B. D., & Halligan, S. (2020). At what times during infection is SARS-CoV-2 detectable and no longer detectable using RT-PCR-based tests? A systematic review of individual participant data. *BMC Medicine*, *18*(1), 346. https://doi.org/10.1186/s12916-020-01810-8

McKinsey & Company. (2021, May 13). *Fast-forward: Will the speed of COVID-19 vaccine development reset industry norms?* McKinsey.com. Retrieved March 22, 2023, from https://www.mckinsey.com/industries/life-sciences/our-insights/fast-forward-will-the-speed-of-covid-19-vaccine-development-reset-industry-norms

Murdoch B. (2021). Privacy and artificial intelligence: challenges for protecting health information in a new era. *BMC medical ethics*, *22*(1), 122. https://doi.org/10.1186/s12910-021-00687-3

Mythen, G. (2004). Defining Risk. Ulrich Beck: A Critical Introduction to the Risk Society. (pp. 53-73). London, England. Sterling, Virginia. Pluto Press.

Nygren, K. G., & Olofsson, A. (2020). Managing the Covid-19 pandemic through individual responsibility: The consequences of a world risk society and enhanced ethopolitics.

Journal of Risk Research, *23*(7–8), 1031–1035. https://doi.org/10.1080/13669877.2020.1756382

Ong, E., Wong, M. U., Huffman, A., & He, Y. (2020). COVID-19 Coronavirus Vaccine Design Using Reverse Vaccinology and Machine Learning. *Frontiers in Immunology*, *11*. https://doi.org/10.3389/fimmu.2020.01581

OpenAI. (2023, February 2). *CHATGPT: Optimizing language models for dialogue*. OpenAI. Retrieved February 5, 2023, from https://openai.com/blog/chatgpt/

Pascu, L. (2020, February 11). *LG CNS collaborates with SenseTime on biometric entry service unaffected by masks*. BiometricUpdate.com. Retrieved March 22, 2023, from https://www.biometricupdate.com/202002/lg-cns-collaborates-with-sensetime-on-biometric-entry-service-unaffected-by-masks

Pietrocola, M., Rodrigues, E., Bercot, F., & Schnorr, S. (2021). Risk Society and Science Education. *Science & Education*, *30*(2), 209–233. https://doi.org/10.1007/s11191-020-00176-w

Piret, J., & Boivin, G. (2021). Pandemics Throughout History. *Frontiers in Microbiology*, *11*. https://doi.org/10.3389/fmicb.2020.631736

Ransbotham, S., & Khodabandeh, S. (2021, July 13). Me, Myself, and AI. *AI and the COVID-19 Vaccine: Moderna's Dave Johnson*. broadcast, MIT Sloan Management Review.

Reuters Staff. (2020, February 21). *Moscow deploys facial recognition technology for coronavirus quarantine*. Reuters. Retrieved March 23, 2023, from https://www.reuters.com/article/us-china-health-moscow-technology-idUSKBN20F1RZ

Artificial Intelligence (AI) – what it is and why it matters. SAS India. (n.d.). Retrieved November 1, 2022, from https://www.sas.com/en_in/insights/analytics/what-is-artificial-intelligence.html

Sohn, R. (2022, April 21). *AI drug discovery systems might be repurposed to make chemical weapons, researchers warn*. scientificamerican.com. Retrieved March 22, 2023, from https://www.scientificamerican.com/article/ai-drug-discovery-systems-might-be-repurposed-to-make-chemical-weapons-researchers-warn/

Su, Z., McDonnell, D., Bentley, B. L., He, J., Shi, F., Cheshmehzangi, A., Ahmad, J., & Jia, P. (2021). Addressing Biodisaster X Threats With Artificial Intelligence and 6G Technologies: Literature Review and Critical Insights. *J Med Internet Res*, *23*(5), e26109. https://doi.org/10.2196/26109

Wang, L., Lin, Z. Q., & Wong, A. (2020). COVID-Net: a tailored deep convolutional neural network design for detection of COVID-19 cases from chest X-ray images. *Scientific reports*, *10*(1), 19549. https://doi.org/10.1038/s41598-020-76550-z

WHO coronavirus (COVID-19) dashboard. World Health Organization. (n.d.). Retrieved February 5, 2023, from https://covid19.who.int/

Yang, Y., & Zhu, J. (2020, February 7). *Coronavirus brings China's surveillance state out of the Shadows*. Reuters. Retrieved March 22, 2023, from https://www.reuters.com/article/us-china-health-surveillance/coronavirus-brings-chinas-surveillance-state-out-of-the-shadows-idUSKBN2011HO

Yuan, S. (2020, March 1). *How China is using AI and big data to fight the coronavirus*. Al Jazeera. Retrieved March 22, 2023, from https://www.aljazeera.com/news/2020/3/1/how-china-is-using-ai-and-big-data-to-fight-the-coronavirus