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Lessons Learned from the COVID-19 Pandemic: A Statistician's Reflection

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Abstract. In this article, I will discuss my experience as a statistician involved in COVID-19 research in multiple capacities in the last two years, especially in the early phase of the pandemic. I will reflect on the challenges and the lessons I have learned in pandemic research regarding data collection and access, epidemic modeling and data analysis, open science and real time dissemination of research findings, implementation science, media and public communication, and partnerships between academia, government, industry and civil society. I will also make several recommendations on navigating the next stage of the pandemic and preparing for future pandemics.

Key words and phrases: COVID-19 research, data collection and access, data analysis, epidemic modeling, implementation science, open science, media and public communication.

1. INTRODUCTION

The COVID-19 pandemic has substantially increased the public's interest in timely data sharing, data access protocols, dashboards, and effective communication of data-driven scientific findings, to a degree that is unparalleled during previous public health events. These activities have reshaped the landscape of data science in helping national and global public health responses to a once-in-a-lifetime pandemic. To this end, I will focus on my experience as a statistician involved in COVID-19 research in multiple capacities, especially in the early phase of the pandemic. I will discuss the challenges and the lessons I have learned regarding data collection and access, epidemic modeling and data analysis, open science and real time dissemination of research findings, implementation science, media and public communication, and partnership between academia, government, industry, and civil society. I will also make several recommendations on navigating the next stage of the pandemic and preparing for future pandemics.

2. GETTING ENGAGED EARLY AND LEARNING ON THE FLY: ANALYSIS OF THE WUHAN COVID-19 DATA

In late January 2020, a few days following the announcement of human-to-human transmission of the disease later named COVID-19, Wuhan entered into an unprecedented *cordon sanitaire*. On a weekend in early February, I wrote a note to my former postdoctoral fellow Chaolong Wang, Professor in the School of Public Health of Huazhong Science and Technology University, located in Wuhan, China, to check on how he and his family were doing during the outbreak. I learned from Chaolong that he and his colleagues had been analyzing the Wuhan COVID-19 epidemic data to help control the outbreak in Wuhan. The first case in the US was reported in Seattle in mid-January, and the first case in Boston was reported in early February. Sensing a plausible spread in the US and other parts of the world, I decided to join them in analyzing the Wuhan COVID-19 data, in order to gain and share knowledge that could help Wuhan, the US, and other countries fight against the disease at a critical time.

Little was known about this new disease at the time. The research team was challenged by trying to perform multiple tasks simultaneously, including real-time data collection in collaboration with the field team and the Wuhan CDC, statistical analysis of the Wuhan COVID-19 epidemiological data, as well as developing new transmission dynamic models suitable for modeling the Wuhan outbreak. The outbreak evolved quickly, and its modeling and analysis had to be done on the fly. The team worked days and nights with the goal of sharing the findings as early as possible to help Wuhan, the US, and the rest of the world combat COVID-19. The World Health Organization announced the COVID-19 outbreak as a Public Health Emergency of International Concern on January 30, 2020, and later as a pandemic on March 11, 2020.

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We finished our manuscript in a few weeks and posted it as a preprint on *MedRxiv* on March 6, 2020 (Wang et al., 2020). This preprint discussed the epidemiological characteristics and the transmission dynamic features of the disease, and summarized multi-faceted public health intervention strategies that were used by Wuhan, including mask wearing, social distancing, lockdown, and centralized isolation and quarantine, which effectively suppressed the outbreak in Wuhan.

The results on the epidemiological characteristics and epidemic modeling were published in *JAMA* in April, 2020 (Pan et al., 2020). The results on the full transmission dynamics of COVID-19 and evaluation of the public health intervention effects using a new Poisson partial differential equation transmission dynamic model, which we called the SHAPIRE model, was published in *Nature* in July, 2020 (Hao et al., 2020). This work was featured in a Nature editorial on the anniversary of the COVID-19 outbreak (Nature Editorial Team, 2021).

Reflection: During a large-scale disease outbreak or health emergency, timely collection and access to high-quality data, real time analysis, and translation of data into evidence to support swift public health actions and decision making, are among the biggest challenges. It is of paramount importance that statisticians are willing to step in and be engaged early, with a mindset of rapidly learning on the fly the subject matter and the relevant though often limited analytic methods, in collaboration with domain scientists, to help make data-driven pubic health strategy and public policy recommendations. As epidemic modeling of infectious diseases is rather specialized and considerably different from commonly used statistical modeling methods, I had a steep learning curve.

Furthermore, collected epidemiological data during the pandemic, especially at the early phase of the pandemic, are often messier than traditional epidemiological studies. We encountered various analytic difficulties and challenges. However, we learned that these difficulties and challenges can be overcome when multi-disciplinary team members are driven by a broad mission to contain the disease and save lives.

Another lesson I learned from working on the Wuhan COVID-19 study is that a fast response has to be made with incomplete information in controlling an outbreak, especially at the early stage. Dr. Michael Ryan, Executive Director of the health emergencies program of the World Health Organization (WHO), led the WHO team responsible for the international containment and treatment of COVID-19. He shared what he learned from combatting Ebola outbreaks at a WHO COVID-19 meeting on March 15, 2020 (Ryan, 2020): “Speed trumps perfection. Perfection is the enemy of the good when it comes to emergency management. Be fast, have no regrets. You must be the first mover. The virus will always get you if you don’t move quickly. If you need to be right before you move, you will never win.” I appreciate this wisdom, which has important implications for analysis of data especially in the early phase of a pandemic, and the application of findings to guide prompt decisions in the face of uncertainty.

3. THE POWER OF OPEN SCIENCE AND REAL-TIME DISSEMINATION OF RESEARCH FINDINGS USING PREPRINT REPOSITORIES AND SOCIAL MEDIA

The pandemic has amplified the important role of preprint repositories and social media in real-time dissemination of scientific results, and has demonstrated the unprecedent impact and reach that open science platforms can have.

After our Wuhan COVID-19 analysis manuscript was posted on MedRxiv on March 6, 2020, I tweeted a summary of the findings on the same day, which was subsequently widely retweeted. The preprint has had 140,000+ views. On March 10, 2020, in response to COVID-19, Harvard University announced undergraduate students to move out by March 15 2020, and classes to be offered remotely after spring break. To help the local community, I presented the results of our Wuhan study in a Zoom seminar at Harvard on March 13, 2020, the last day before our spring break, and a Zoom seminar at the Broad Institute of Harvard and MIT on March 20, 2020. The seminars provided the community with an overview of the Wuhan outbreak, the multi-faceted intervention measures used in Wuhan along with an evaluation of the effectiveness of these control measures, the risk factors associated with the virus infection, and the identification of vulnerable groups that needed to be protected, such as healthcare workers (HCWs) and elderly people. The seminar recording was made quickly available to public in YouTube and attracted many viewers (25,700+ views).

I showed in my March 13 Zoom talk using the Wuhan data that HCWs were at a higher risk of infection, especially in the absence of interventions, and demonstrated that Personal Protective Equipment (PPE) for HCWs in the US was inadequate compared with what was being used in Wuhan, for example, lacking of medical goggles, face shields, and full protection suits in US. To my surprise, the three slides conveying this message in my March 13 talk were widely distributed during the weekend among HCWs in the US. In response to this talk, on March 16, a few physicians launched a national petition that called for comprehensive PPEs for US HCWs, which resulted in >2 million signatures, and a national PPE drive. The photo in my slide was used in this petition. It is the best reward for a statistician when data analysis results can help people in need at a critical time.

During the pandemic, many teams and volunteers made extraordinary efforts to create COVID-19 dashboards to track COVID cases and deaths in real time, making them freely available to the public. Examples include

- Johns Hopkins Coronavirus Resource Center data (https://coronavirus.jhu.edu/),
- COVID Tracking Project (https://covidtracking.com/),
- USA Facts (https://usafacts.org/), and
- Our World in Data (https://ourworldindata.org/coronavirus).

I was touched by the community spirit of these efforts.

In June 2020, led by my former student Andy Shi in collaboration with several students and postdocs, my own lab launched a COVID-19 Spread Mapper, an online dashboard for estimating, quantifying uncertainty in, and visualizing the daily effective reproduction number R_t, case rate, and death rate at subnational and national levels across the globe (Shi et al., 2022). Our open-source website, Visualizing COVID-19 Spread Metrics (https://metrics.covid19-analysis.org), continues to provide real-time reporting of multiple COVID-19 metrics in an interactive dashboard that can be easily used by the general public, while accounting for case and death reporting delays and differences between weekdays and weekends. This site was featured by Nature in July 2020 (Adam, 2020), and has attracted tens of thousands of users worldwide.

These COVID-19 dashboards have served as vehicles for public education and policy making. Many data scientists talked to mainstream news outlets and used social media to explain and contextualize the visualizations on these dashboards to help the general public understand global and national trends. Soon, terms such as R values became dinner-table topics for many people.

Reflection: The global health emergency created by the pandemic has resulted in real time dissemination of scientific findings at an unprecedented speed via preprint repositories, such as BioRxiv and MedRxiv, and in social media venues, such as Twitter. For example, over 6700 COVID-19-related preprints were posted between January and April, 2020 (Fraser et al., 2021). Open science platforms help scientific findings draw timely and widespread attention from the scientific community, the general public, press, and policymakers, guiding timely and evidence-based public health responses, and directing individual behavior. In the last two years, we have observed that real-time dissemination fortifies the position of preprints and social media in the firmament of scientific communication and elevates their status during a public health crisis.

The spirit of open science has emerged as a hallmark of the fight against the pandemic. The unparalleled efforts in sharing knowledge, data, and resources to combat the pandemic without worrying about credit, especially in the early phase of the pandemic, are likely to have a longstanding and profound impact on the international scientific community, and will help accelerate our ability to study COVID-19 epidemiology, interventions and treatments, and scientific discovery more broadly. In the last two years, especially in the early phase of the pandemic, there has been a strong sense of emergency in the scientific community compelling researchers to provide open access data and resources to the world. Many new cross-disciplinary collaborations have been developed. For example, I got to know many more scientists and policy makers I had never met through conventional venues. This will outlast the pandemic and become a staple not only of epidemiology or epidemic response, but also public health and biomedical science, and data science, more broadly.

4. STATISTICIANS NEED MEDIA AND PUBLIC SERVICE COMMUNICATION TRAINING

In March 2020 after our Wuhan epidemic analysis preprint was widely circulated, I received a good number of media interview requests. Without media training, I initially turned down many interview requests. In April 2020, the virus became more widely spread and the pandemic situation became worse. There was a pressing need to educate the public and policy makers to jointly fight against the pandemic more effectively by explaining the findings and the lessons learned from our Wuhan study. I decided to take media interviews. I was interviewed by many media outlets, including Nature, Science, New York Times, Wall Street Journal, CBS, BBC Radio 4, Newsweek, and Telegram.

In spring, 2020, I served on the State of Massachusetts COVID-19 task force. I discussed the findings of the Wuhan study and the lessons learned from the Wuhan outbreak response with the MA COVID-19 task force. I worked with the task force, which consisted of an interdisciplinary team, including infectious disease specialists, clinicians and public health researchers, and state public health officials, on preparing a report for the MA governor that provided a series of recommendations and strategies for the state, including testing and multi-faceted control measures. I also worked with state officials on ordering and shipping large quantities of PPEs, swabs, and test kits from China for the state of Massachusetts.

Following my initial outreach efforts on the national level, I was invited by the Science and Technology Committee of the UK Parliament to serve a witness on April 17 and discuss the findings of the Wuhan study and lessons learned at one of its COVID-19 evidence sessions. The Committee later made ten recommendations in a letter to the UK Prime Minister Boris Johnson (Clark, 2020), including several of my recommendations.

Reflection: As many have stated, statisticians play an important role in evidence-based public policy making. To effectively engage in helping with public policies, my pandemic experience suggests that media and public service communication skills are of paramount importance, and that statisticians need media and public service training in order to effectively communicate statistical findings and influence public policy. Prior to the pandemic, I had not had media training and had little experience in government testimony. It was a steep self-learning curve for me.

Based on my experience, to be an effective public communicator, one has to learn how to help the public and government officials understand a study, including data, analysis, key findings, and present these and recommendations clearly, without jargon, and in the most basic of plain-language terms. For live interviews on TV and radio and government testimonies, one also needs to learn how to get key messages across clearly in layman terms in only a few minutes. Indeed, it is important to keep the message simple, short, and focused, and to stick with what you know. One also needs to be prepared to answer challenging questions under the scrutiny of investigative journalists and TV hosts.

5. PARTNERSHIP BETWEEN ACADEMIA, GOVERNMENT, INDUSTRY, AND CIVIL SOCIETY

In spring 2020, I collaborated with Dr. Feng Zhang, Professor of Neuroscience and Core member of the Broad Institute of MIT and Harvard, the CEO of Pinterest Ben Silbermann, and a group of software engineer volunteers at Pinterest and other organizations to launch an independent, nonprofit organization called The How We Feel (HWF) Project, which supported the development of a HWF app. I served as the PI of the HWF Project. The HWF app collected longitudinal data from users on demographics, COVID-19 exposure, pre-existing medical conditions, symptoms, test results, behavior and sentiment. By leveraging the team's complementary expertise, the app was rapidly developed and launched in a few weeks in spring 2020 and was made freely available for download in both Apple Store and Google Play. The app has had 575,000+ users in the US and worldwide, and has collected 15+ million longitudinal responses.

In the spring of 2020, the HWF team developed a partnership with the State of Connecticut, which helped attract a large number of users from Connecticut. The HWF team met with the CT Department of Public Health regularly in 2020 to share the findings. We published the first findings of the HWF project in Nature Human Behavior in the summer of 2020 (Allen et al., 2020), which reported the risk factors for COVID-19-related symptoms and positive tests, and highlighted the temporal dynamics of symptoms and self-isolation behavior. Researchers are able to apply for access to HWF data through the nonprofit organization HWF Project.

Reflection: The COVID-19 pandemic has driven unprecedented levels of partnership between academia, government, industry, and civil society to address global health challenges. These partnerships have achieved societal benefits by enabling the effective integration of the strengths and expertise of diverse partners. They have resulted in the rapid development of digital tools or platforms for real-time data collection, analysis, and sharing, as well as development of new vaccines and therapies. They have helped promote transdisciplinary collaboration in research and innovation, community outreach, and public policy, leading to great societal benefits. Strategically fostering such partnerships in years ahead will improve our chances of better preparing for future pandemics and making health for all a more realistic and much more sustainable goal.

In addition, the last two year research experience has also shown that, to effectively respond to future pandemics, inter-disciplinary collaborative efforts are needed in the areas of statistics and data science, biomedicine, epidemiology, behavior science, health policy and global health. All of these fields play important roles in informing COVID-19-related public health decisions and practice.

6. CHALLENGES IN EPIDEMIC MODELING OF US COVID-19 DATA AND STRATEGIES FOR BETTER DATA COLLECTION AND INFRASTRUCTURE BUILDING TO PREPARE FOR FUTURE PANDEMICS

In the summer of 2020, I started engaging students and postdoctoral fellows in my lab in several COVID-19-related projects, including analysis of publicly available country, state, and county- level COVID-19 data, and individual level data collected from the How We Feel Project. Students and postdocs were highly enthusiastic about participating. We had weekly COVID-19 lab meetings discussing data and analysis-related issues and results. Two of my postdoctoral fellows took the lead in analyzing the aggregated US state-level COVID-19 data. We published a discussion paper in the December issue of Journal of the American Statistical Association in 2021 (Quick et al., 2021), which proposed a Multilevel Epidemic Regression Model to Account for Incomplete Data (MERMAID). It provides a regression framework that jointly estimates the effective reproductive number R_t, ascertainment rates, incidence, and prevalence over time in one or multiple regions by incorporating geographic and time-varying covariates. MERMAID accounts for under-ascertainment by modeling the ascertainment probability over time as a function of testing metrics using data on confirmed infections and population-based serological surveys, as well delays between infection, onset, and reporting by treating lag times as missing data.

We applied MERMAID to analyze COVID-19 daily confirmed infection counts, PCR testing data, and serological survey data across the United States. We estimated an overall COVID-19 prevalence of 12.5% and an overall ascertainment rate of 45.5% in the US from March to December 2020.

From the start of the pandemic, far more COVID-19-related data have been made available in greater detail and in real time, than in any previous pandemic or disease outbreak. However, our experience in analyzing the US COVID-19 data demonstrated that data are often messy and there are substantial challenges in collecting and curating meaningful and reliable national and subnational COVID-19 cases, deaths and testing-related numbers during the pandemic.

Among the discrepancies we found were, first, that daily reported infection and test counts showed substantial discordance between different data sources in several states. Second, reported COVID-19 infection and test data showed backlogs and some consistent irregularities across data sources, which likely did not reflect true patterns in infections. For example, sporadic lapses in reporting and strong weekday effects were evident for many US states. Third, while serological surveys provided a vital secondary means of estimating the prevalence of COVID-19, they provided prevalence estimates that were significantly higher that those based on the confirmed infection numbers using the PRC test data. In addition, age and race- specific case and death aggregated data were not available during the early phase of the pandemic. They later became available at the state level for most of the states, but were not available at the county level. This made sub-national analyses on health disparity challenging.

For individual-level observational study data collected during the pandemic, such as the How We Feel data, selection bias was a significant challenge. For example, in spring 2020, respondents who were eligible for being tested were more likely to have symptoms, to be older, and were more likely to be health care workers and essential workers (Allen et al., 2020). Our analysis hence needed to take this selection bias into account. Selection bias was also observed in several other large digital surveys (Bradley et al., 2021).

Reflection: We have observed substantial challenges in collecting both aggregated national and subnational data and individual-level data during the pandemic. Gold standard epidemiological data collection protocols, such as random population-based sampling, were much needed but have been quite challenging to implement in the real world, due to various practical constraints in the last two years. Numerous calls have been made for better quality data (Jewell, 2021, Dean, 2022). Indeed, statisticians' best analytic efforts cannot fully overcome the major limitations of real-world data, including data incompleteness, inaccuracy, and biased sampling.

Concerns have recently been raised that various COVID data projects are seen as one-off efforts. Some dashboards, such as the COVID Tracking Project, have already stopped functioning. Government efforts to collect and display data in real time are slowing in many parts of the world (Nature editorial team, 2022). With emerging variants and populations of many developing countries not yet vaccinated, these cutbacks could have adverse consequences for the world for the next stage of the pandemic.

Public-health decisions need to be informed by the best available data in order to build public trust and transparency. To allow data to better inform policy, our pandemic experience in the last two years demonstrates the need for building coordinated and effective national and international surveillance, testing, and sequencing systems, to ensure the completeness and representativeness of data collection and reporting, as well as data collection consistency and comparability over time and among regions. Aggregated national and subnational data should be made freely available, and should be both standardized and machine-readable, in real time. Systems need to be developed so that age, gender, race, and ethnicity stratified aggregated data at national and subnational levels can be collected and made more available.

It is encouraging that innovative designs have already emerged from data collection challenges, such as wastewater surveillance of COVID-19 (Larsen and Wigginton, 2020), which provides real-time information on whether virus levels are increasing or decreasing across a community without relying on individual test results. However, wastewater surveillance results cannot pinpoint infected individuals in a community. Building global disease surveillance infrastructure that facilitates data collection at the national and subnational level and individual level using emerging technologies and representative sampling schemes will help navigate the next stage of the pandemic and prepare for future pandemics.

7. IMPLEMENTATION SCIENCE IS EQUALLY IMPORTANT AS DATA SCIENCE

The COVID-19 pandemic highlights the critical role of data science in informing evidence-based policies for disease surveillance and control. However, data science alone is insufficient to successfully fight against a pandemic. The COVID-19 pandemic shows that implementation science is equally important as data science. Public health control measures and vaccination are a key for combatting the pandemic, but their effective implementation has been quite challenging in many countries. The last two years have taught us that using data to show the public health intervention tools work for controlling disease spread in real-world studies is not sufficient. Implementation science helps bridge the gap between research and practice.

In the early phase of the pandemic, counties that were successful in containing the pandemic were those that were effective in implementing multi-faceted public health control measures with high compliance. This required decisive leadership, solidarity, coordination, effective implementation, and cooperation of the general public. The pandemic has demonstrated that behavioural changes are difficult, but also that humankind has inherent interdependence. Effective and rigorous implementation of public health control measures such as mask wearing, social distancing, isolation and quarantine, and vaccination rollout with high compliance, is challenging without solidarity, understanding of region-specific human behavior and culture, and the assumption of shared responsibility by all the stakeholders. As a consequence, the virus has had an enormous impact on people's life, health systems, and economies in many countries.

We need to develop better implementation science strategies for public health control measures and vaccination programs that are tailored towards the situation and culture of individual countries and regions. This will require not only more research in behavior science, leadership, and coordination at all levels, but also clear public communication, and partnership among all stakeholders.

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