TWO

Breakthrough Technologies for Pandemic Preparedness

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In March of 2020, COVID-19 was officially declared a global pandemic, rapidly exposing gaps in public health systems worldwide and intensifying the inequalities that disproportionately affect marginalized communities everywhere. Scientists and public health experts warned for years of an imminent, deadly, and rapidly spreading virus, identifying potential geographical hotspots for its origin and devising plans to catch and contain it.[1] Previous outbreaks, such as SARS in 2002, Ebola in 2014, and Zika in 2016, continuously reminded us of the need to shore up our global pandemic preparedness infrastructure. But as recently as 2019, not one country had built a strong enough national pandemic preparedness system to stave off or contain a potential epidemic, according to the Global Health Security Index.[2]

Today, the world is on the cusp of a new era. Thanks to modern advances in biomedicine and information science, we have the capacity to build a systematic approach for detecting and tracking outbreaks of common and fatal infectious

1. McKay and Dvorak.
2. Prevent Epidemics.

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diseases, and preventing novel ones from emerging. To make this vision a reality and achieve global pandemic preparedness, two main pillars of progress are key (see table 2-1). The first pillar is advances in biomedical and genomic technologies that can detect virtually any pathogen; produce simple, point-of-care diagnostics that can be deployed anywhere in the world; and enable rapid development of countermeasures such as vaccines and therapies. The second pillar incorporates powerful new information systems and data collection tools that allow real-time viral surveillance, data sharing, and integration of health systems, on both a regional and global level. These tools also open a critical pathway for public health officials to interface with communities, respond to needs, and provide real-time information on the trajectory of the virus.

This chapter explores breakthrough technologies that comprise each pillar, in the context of the existing recommendations for global governance and coordination of pandemic preparedness, including those provided by the Independent Panel for Pandemic Preparedness and Response (IPPPR), as well as the G20 High Level Independent Panel on Financing the Global Commons for Pandemic Preparedness and Response. Given that most of the technologies we describe are

Table 2-1. Pillars for a Breakthrough in Pandemic Preparedness

Pillar 1	Biomedical and Genomic Advancements	Detection Tools (for example, PCR and antibody tests; LAMP; CRISPR-based SHERLOCK, DETECTR, and HOLMES; and synthetic biology-based INSPECTR)
		Countermeasures (for example, monoclonal antibodies and vaccines, including mRNA vaccines and ongoing R&D for universal flu vaccine)
Pillar 2	Information Technologies	Public Health Response Tools (for example, CommCare; DHIS2)
		Citizen Data Capture Tools (for example, Flu Near You; Outbreaks Near Me)
		Proximity Sensing Tools (for example, GAEN API by Apple and Google; NOVID)
		Forecasting Networks (for example, Infectious Diseases Modeling Team at the National Institute for Public Health and Environment in the Netherlands; Scientific Advisory Group for Emergencies in the United Kingdom)

already available in most advanced economies and to varying degrees in low- and middle-income countries (LMICs), this chapter also elucidates the foundational elements that allow them to translate effectively to pandemic preparedness in advanced economies and LMICs alike. First, a centralized and well-coordinated public health infrastructure, with policies that promote inter- and intra-agency collaboration, are critical, but too often lacking in LMICs and advanced economies. Second, equity and community empowerment must underline the rollout of both pillars. Third, adequate and sustainable financing are key, which may be lacking in LMICs or ineffectively distributed and prioritized in wealthier economies.

Global Coordination for Pandemic Preparedness

A vastly improved global approach is within reach. By 2030, every country should enjoy the fundamental building blocks of pandemic preparedness, including the capacity to sequence emergent threats, the expertise and resources to rapidly build diagnostics, treatments, and vaccines, and the infrastructure to both surveil viral spread locally and share data in real time. Because viruses are so fast-moving, penetrating, and volatile, no country can be left behind if we are to successfully preempt another global pandemic. Pandemic preparedness and response require the full participation of every nation and must be undertaken with the precision and speed of military alliances such as NATO, the diplomatic tact of the World Health Organization (WHO), and the inclusive nature of the United Nations General Assembly.[3] To achieve this vision, governance and coordination are key. Among the many recommendations outlined by the IPPPR and G-20 High Level Independent Panel, there emerges a common theme: strengthening global leadership and coordination at every level for pandemic preparedness—from building and improving surveillance systems to developing "pre-negotiated" platforms for production and distribution of tests and medical countermeasures—with financing as a key facilitator.[4]

Even before the next outbreak or pandemic strikes, immediate action to advance the recommendations of both panels are critical for a number of reasons. Most evidently, infectious disease has generated more personal and economic devastation than any war in modern history. Every year, the impacts of annual infections eclipse those of all major wars, but traditional defense budgets, including that of the United States, contribute very little to combating the bioterror threat posed by infectious pathogens. The cost of crisis response, once a major

3. Osterholm and Olshaker.
4. Independent Panel for Pandemic Preparedness and Response.

outbreak hits, far exceeds that of building resilient health systems for pandemic preparedness. In 2016, the Commission on a Global Health Risk Framework for the Future explained why an additional US$4.5 billion dedicated to pandemic preparedness each year would considerably improve global resilience against infectious disease.[5] By comparison, the 2014–16 Ebola outbreak in West Africa cost an estimated US$53 billion in economic losses and 11,300 deaths.[6] One year into the COVID-19 pandemic, estimated economic losses thus far have reached several trillions of dollars and deaths have surpassed 4 million, with extensive morbidity beyond.[7,8]

Furthermore, the tools needed to stop a viral outbreak are broadly applicable to any virus and routine care. Pandemic preparedness is not separate from, but rather core to, a healthcare system capable of fighting malaria, TB, neglected tropical diseases (NTDs), and the common cold. Anywhere in the world, the tools needed to stop our families, neighbors, and coworkers from falling ill are the same tools needed to stop an outbreak. Both pandemic preparedness and general healthcare work hand in hand to improve health and wellness worldwide.

Finally, our universal vulnerability to infectious pathogens, made evident by COVID-19, means that everyone has an important role to play in outbreak prevention. Because of the exponential spread of viruses, one person can launch a pandemic, but one person can also stop it from spreading. To avoid future devastation, the global community must unite now in empowering every actor in the system to fully engage in their own health. This means eliminating global disparities in access to detection tools, countermeasures, and information technologies, connecting local health systems and providers with national, regional, and global health systems, and building newfound community trust in science and medicine.

Pillar 1: Biomedical Advances in Detection and Countermeasure Technologies

Biomedicine has undergone a recent revolution that transformed our ability to identify and characterize a virus—that is, detection—as well as our ability to treat and prevent it—that is, countermeasures. One of the key technologies that underlies this revolution is genome sequencing, which allows us to detect and characterize novel threats and informs the design of targeted diagnostics, treatments, and vaccines.

5. Commission on a Global Health Risk Framework for the Future and National Academy of Medicine, Secretariat.

6. Miles.

7. Cutler and Summers.

8. World Health Organization, 2020c.

Detection Technologies

When a virus first enters a human population, containment hinges on rapid and accurate detection. Once it is detected and characterized, a distributed and reliable diagnosis is the foundation of pandemic preparedness and response. This is partly because many infectious diseases present with overlapping symptoms, so precise, an early diagnosis is necessary to prescribe appropriate clinical or public health measures. It is also because some infectious diseases spread through asymptomatic or presymptomatic carriers, like COVID-19, of which 20 percent of transmission comes from cases that are asymptomatic and 30–40 percent from those who are presymptomatic, meaning that those infected may spread the virus without knowing. Thus, widespread early detection efforts are critical to containment.[9, 10] Moreover, early detection can reverse the course of a disease by signaling the need for lifesaving treatment, like in the case of Lassa fever, where early treatment has reduced case fatality from 55 percent to 5 percent.[11]

The first major breakthrough in our ability to detect viruses is genome sequencing, which allows us to identify and characterize the genome of viruses circulating in clinical and environmental samples and to gain continual insights into their genetic diversity, evolution, and transmission. For example, within a month of COVID-19 entering the human population, genome sequencing allowed Chinese scientists to identify and characterize SARS-CoV-2—the causative agent. Since then, there have been over 3.4 million genome submissions and counting, as of September 2021, to GISAID, the publicly accessible global database, which have helped uncover patterns of transmission (for example, super-spreader events, increases in virus transmissibility) and identify variants of concern.[12]

Traditionally, scientists have relied on two kinds of diagnostics—polymerase chain reaction (PCR) and antibody tests. A classic molecular diagnostic, PCR works by extracting genetic material (DNA, RNA) from a sample, which is then copied several times over to confirm or negate the presence of a virus. It is sensitive and specific, suitable for clinical testing, and readily adaptable to new infectious pathogens.[13] Alternatively, antibody tests can detect either the virus or antibodies to a virus. This group includes antigen capture tests, often used as point-of-care tests, which use antibodies that bind to viral proteins and other elements to signal if they are present in a patient's body.[14] Another type of antibody test, classic serology tests, determine if a patient is currently mounting

9. Buitrago-Garcia and others.
10. Citroner.
11. McCormick and others.
12. GISAID.
13. Botti-Lodovico and others.
14. Centers for Disease Control and Prevention.

Table 2-2. Major Barriers to Implementation

Pillar 1	Deployability	Some detection tools such as PCR require sophisticated and bulky machinery, limiting deployability in low-resource settings. Cold chain requirements add additional obstacles to COVID-19 vaccine delivery.
	Time to Develop	Antibody tests and vaccines can take months or years to develop. As the virus evolves, tests, treatments, and vaccines must adapt along with it. Regulatory approval processes can be slow and cumbersome.
	Cost/Access	Clinical grade PCR tests for COVID-19 can cost from US$25 to thousands of dollars, and even in advanced economies, too few laboratories have the capacity to build and validate their own PCR tests.
Pillar 2	Connectivity and Digital Divide	Frontline healthcare workers and health departments across the globe often still rely on pen, paper, e-mail, and/or bespoke electronic medical systems to record, share, and communicate data, due to limited internet access or lack of ability to update systems.
	Voluntary Buy-In	Lack of trust and understanding within communities around the role of information technologies, as well as their use and rights to privacy, can thwart buy-in, making citizen reporting less effective and sometimes even misleading.
	Interoperability	The existing range of information technologies often do not communicate with each other in a seamless fashion. There is still no global public database for reporting and storing COVID-related patient data.
	Data Modeling Capacity	Data-modeling capacity needs improvement in regions across the globe, particularly in LMICs, and scientists need a centralized infrastructure to regularly coordinate and share information with policymakers.

an immune response or previously had an infection that left memory antibodies. Both classes face barriers to implementation (see table 2-2). PCR requires sophisticated machinery, thereby limiting its deployability; and antibody tests—like the U.S. FDA-approved antigen test for COVID-19—require bespoke development, which often takes several months.[15]

New technologies are emerging that have enabled increased diagnostic development and operability in lower-resource settings worldwide. Thanks to genomic advancements and new discoveries around isothermal amplification, CRISPR, and synthetic biology, scientists have developed a range of new, ultrasensitive, low-cost, rapidly programmable, and widely deployable point-of-care diagnostics. Isothermal amplification technologies such as LAMP (Loop-Mediated Isothermal Amplification) operate similarly to PCR, but at a single lower temperature, so that they can be performed with minimal equipment. As a test, LAMP was found to be highly specific, scalable, and cost-effective, and can produce results within an hour (compared to the four to eight hours required by PCR methods).[16, 17] CRISPR, which consists of a guide protein and nuclease originally discovered in nature as a bacteria's immune system to viruses, has been paired with isothermal amplification to enable the development of even more sensitive, fast, and portable diagnostic tests, such as SHERLOCK, DETECTR, and HOLMES.[18, 19] The synthetic biology-based INSPECTR—a molecular diagnostics platform—has also enabled accurate and specific viral detection on a portable and affordable lateral flow test strip.[20] Meanwhile, efforts to accelerate the development of antibody tests have been underway to prepare for new and emerging threats, and could provide a viable option for household testing kits by 2030.[21]

Countermeasures

Prior to the genomic advancements described above, the development of medical countermeasures was slower, more experimental, and less precise. Traditionally, therapies were often discovered in nature and had to undergo a long evaluation process to understand effects on patients. Classic vaccines required a complex process of inactivation of the antigen or viral protein—that is, the

15. Hahn and Shuren.
16. Dao Thi and others.
17. Kashir and Yaqinuddin.
18. Chen and others.
19. Li and others.
20. Wyss Institute.
21. Baraniuk.

part of the virus that induces production of antibodies—to trigger a natural immune response, and development generally took up to a decade before safe public deployment was possible.[22] Today, with the unprecedented ability to target pathogens based on their genome, countermeasure development has been faster, more innovative, and more specific than ever before. Examples of treatment and vaccines made possible by genomic advancements include monoclonal antibodies, messenger RNA (mRNA) vaccines, and universal vaccines to target all types of flu and coronavirus.

Monoclonal antibodies underlie treatments for HIV, Zika, Ebola, MERS--COV, RSV, influenza, and COVID-19.[23] Scientists can manufacture monoclonal antibodies to imitate the effects of naturally produced antibodies that arise as a result of viral infection. In the context of COVID-19, administering monoclonal antibodies has been found to reduce hospitalization rates, especially if given to patients early in the onset of illness.[24] Today, microbiology experts have proposed efforts to begin producing monoclonal antibodies that can defend humans against one hundred of the most probable future epidemics, allowing faster disease response and mitigation.[25]

In parallel, scientists have developed a host of novel vaccines based on genomics, such as DNA and RNA vaccines. Particularly relevant today, the mRNA vaccine is one example of a DNA/RNA vaccine that has revolutionized our ability to prevent transmission of SARS-CoV-2. The injected mRNA gives the host immune system directions to produce and present SARS-CoV-2's spike protein, and thus generate antibodies against the virus.[26] These vaccines are safe for humans, because mRNA is compact and specifically processed for expression, making it easy to deliver and less likely to affect the host genome when injected.

Scientists are also working to develop a universal influenza vaccine, and may eventually venture toward developing a universal coronavirus vaccine to prepare against new variants of each.[27] Such vaccines would provide wider immunity by targeting the stem of the virus, a part that varies less between different strains. One candidate vaccine for influenza, H1ssF_3928, is currently undergoing evaluation at the National Institute of Allergy and Infectious Diseases (NIAID).[28]

22. Hubaud.
23. U.S. Food & Drug Administration.
24. Edwards.
25. Weintraub.
26. Empinado.
27. Weintraub.
28. National Institutes of Health.

Pillar 2: Information Technologies

In 2015, the WHO Ebola Interim Assessment Panel announced a broad need for "innovations in data collection . . . including geospatial mapping, mHealth communications, and platforms for self-monitoring and reporting."[29] More than five years later, there is still no global public database for reporting and storing COVID-related patient data, according to a *Lancet* report from May 2020.[30] Due to limited internet connectivity and the ongoing digital divide, frontline healthcare workers and health departments across the globe depend on e-mail, paper, and/or bespoke electronic medical systems to record, share, and communicate data.[31] Data modeling capacity, another critical piece to outbreak preparedness, needs improvement in several LMICs, particularly in Africa, while scientists in even advanced economies sometimes lack a centralized infrastructure to coordinate and share this information with policymakers in a seamless and rapid manner.[32,33]

Pillar 2 is critical because the most successful COVID-19 containment stories came out of regions that prioritized a combined test-and-trace approach. This approach not only elevates hypothesis-driven testing (that is, symptomatic cases and their contacts), but also regularly *informs* public health experts on the movements, behaviors, and needs of communities amid an outbreak, as well as the likely evolution and trajectory of the virus. Three categories of breakthrough information technologies, in addition to data-driven forecasting networks, can together help facilitate outbreak containment.

First, a range of professional public health tools, already embedded in communities, are empowering responses worldwide. Recently enhanced for COVID-19 response, these tools help public health workers accelerate surveillance efforts, and analyze and share data in real time. CommCare and District Health Information Software (DHIS2) are two examples. CommCare is an open-source, data collection platform operationalized for mobile data gathering and reporting in eighty countries.[34] It enables public health workers to access data from an individual's phone, connect with the contacts of a patient, and request individual symptom reports by WhatsApp or SMS. These reports are then passed on to the relevant healthcare providers and public health departments to inform necessary measures for containment. DHIS2 is another integrated, centralized system that enables data

29. Colubri and others.
30. Cosgriff and others.
31. Sabeti and Salahi.
32. Travaly and Mare.
33. Rivers and George.
34. Dimagi.

management, analysis, logistics management, and mapping of health services for communities in a given nation or region. It can function offline and is currently operating in seventy-three LMICs, facilitating data-driven public health measures and connecting stakeholders at every level of the healthcare system.[35]

Second, a range of integrated tools for capturing citizen data and empowering communities have been developed, many operating through smartphone-based mobile applications. Examples include Flu Near You, available in the United States and Canada, and Outbreaks Near Me, available in Mexico, Canada, and the United States. Both rely on crowdsourcing data from individuals who elect to report their symptoms and health status online. That information is then used to produce real-time visualizations of citizen data, which can help epidemiologists and health officials better understand COVID-19 transmission in target areas and alert individuals when a case has been confirmed in their geographical area.[36]

Third, proximity-sensing technologies are another option for enabling more accurate contact tracing and surveillance. Some of these technologies use Bluetooth for proximity sensing, such as Google Apple Exposure Notification (GAEN) application programming interface (API), which enables governments and the public health community to send smartphone alerts to individuals if they have been exposed to an infected individual.[37] Another proximity-sensing tool, NOVID, created by Carnegie Mellon University, combines Bluetooth with ultrasonic technology, to determine with an even higher degree of accuracy the level of contact one has made with an infected individual.[38] As mobile phone use continues to increase, with 67 percent of the entire world population owning a mobile phone (and 65 percent owning a smartphone) in 2019, all of these applications are proving more relevant today.[39]

Finally, forecasting networks are another breakthrough tool that combines epidemiological surveillance with predictive modeling and coordinated data analysis around a range of factors, including host and agent mobility, healthcare institutional capacity, virus transmissibility, and population density.[40] They systematically forecast the potential number of cases that could arise in a certain location over time, determine and assess various interventions, and identify areas of high need. Existing models include the Infectious Diseases Modelling Team at the National Institute for Public Health and the Environment in the Netherlands, and the Scientific Advisory Group for Emergencies in the United Kingdom.[41]

35. DHIS2.
36. Jacobs.
37. Landi.
38. Payne.
39. Budd and others.
40. Wick.
41. Rivers and George.

Case Studies: Low-Income vs. Advanced Economy

This section explores how two countries at very different stages of economic development—Liberia and South Korea—applied the essential pillars of pandemic preparedness and, to varying degrees, the breakthrough technologies discussed. As a low- and high-income economy, respectively, they each provide a model for how similarly positioned nations might build pandemic preparedness, with the help of the global community to fill resource and capacity gaps where needed.

Liberia

In a review of national responses to COVID-19 from early 2021, Tom Frieden, former director of the U.S. CDC, designated Liberia as the "best at learning from recent epidemics," noting only one COVID-19 death out of every 55,040 Liberians, compared to one death out of every 990 Americans over the same time period.[42] Despite having one of the most resource-poor health systems in the world, Liberia had already instituted many of the public health policies needed to facilitate an effective COVID-19 response. Their approach was centralized and unified, marked by strong and effective leadership. With a great deal of political will driven by memories of the Ebola outbreak of 2014–16, national leadership rapidly set out to build the "coronavirus task force," a committee that focused on reviving the core foundation that powered their previous outbreak response.[43, 44] This involved an aggressive strategy of rapid testing, contact tracing, and imposed quarantine where needed.[45]

With the necessary infrastructure and human capacity in place, scientists began rapidly implementing PCR tests,[46] while the government obtained additional tests from the WHO to fill gaps in local laboratory capacity.[47] Contact tracing and data gathering was coordinated under the Active Case Finders and Awareness Team, but due to a lack of broad connectivity and local preferences, the Liberian approach was dependent on "door-to-door" interaction and community-based prevention techniques, designated as "active case finding."[48] In concert with trusted community health workers, contact tracers were able to deliver information on the virus, build trust, and respond to community

42. Frieden.
43. Maxmen.
44. Wallace.
45. Frieden.
46. World Health Organization. 2021b.
47. Maxmen.
48. Winny.

concerns—something that many advanced economies failed to do. Their COVID task force also shared data and met periodically to enable adaptations in their approach, based on evolving needs.[49]

As in many LMICs, Liberia has faced challenges with the higher tech components of pandemic response, including the near real-time data gathering and contact tracing capabilities achieved through information technologies and widespread connectivity. Like many other nations, they have also experienced shortages of tests.[50] The World Bank and others provided assistance earlier on in the pandemic, including a grant worth US$3.75 million, as well as a concessional International Development Association (IDA) credit of US$3.75 million to build capacity in local laboratories, facilitate coordination and collaboration, and support the Liberian government's outbreak response measures.[51] Ultimately, more financial and infrastructural assistance is needed both now and in the long term for Liberia to overcome COVID-19 and achieve long-term pandemic preparedness. Yet their comparative success and focus on community needs provide a hopeful model for LMICs and advanced economies alike on how a well-coordinated, prepared, and aggressive approach to infectious pathogens can transform outbreak response.

South Korea

In the same review cited above, Frieden designated South Korea as "best at testing," noting only one COVID-19 death out of every 63,290 Koreans. Early on in the outbreak, Korean leadership established an aggressive and highly coordinated testing strategy, allowing the nation to deploy double the number of tests per capita in the initial weeks after the pandemic began, compared to other nations.[52] Their speed in response can be largely attributed to the outbreak response infrastructure they developed during the MERS outbreak in 2015, as well as their preexisting genomic capacity, strong leadership from the Korea Disease Control and Prevention Agency, and a revamped emergency process that sped up the approval time for diagnostics from a year to a week or under.[53]

The information technology and data integration pillar has been driven by the extraordinary levels of connectivity in South Korea, as well as a preexisting "legal and cultural framework" that facilitates highly accurate contact tracing

49. Maxmen.
50. Ibid.
51. World Bank.
52. Frieden.
53. Campbell and Lee.

and epidemiological surveillance.[54] According to a recent Brookings post by Justin Fendos, more than 96 percent of Koreans enjoy daily access to the internet, while approximately 95 percent have a smartphone.[55] To better target testing and contact tracing, Korea's post-MERS amendment of the Infectious Disease Control and Prevention Act enabled health authorities in times of outbreak to access the same information on citizens that police can access for law enforcement purposes. On average, citizens are largely amenable to the regulated use of their personal data to keep themselves and their families safe, including information gathered from mobile devices and location logs, surveillance footage in public spaces, and electronic transactions. Citizens also receive alerts when they may have come into contact with an infected individual, which empowers them to seek testing if necessary.

While South Korea has had challenges containing the virus, their aggressive detect-and-connect strategy has enabled them to evade a strict lockdown since the start of the pandemic, without the devastating consequences of rampant viral spread.[56] Thanks to a strong preexisting public health infrastructure, mass community buy-in, and the resources needed to broadly finance these efforts, technological progress proved invaluable to the pandemic response in South Korea. Further, the trust citizens had in their government and public health system proved to be a critical factor in empowering communities to fully engage in pandemic response.

Priorities for Implementation

Thanks to advances in genomics and information technology, scientists have developed tests, vaccines, and tools at record speed amid COVID-19, proving that the world can prepare for the next pandemic if incentives are aligned. Success stories in contexts as different as Liberia and South Korea provide insight regarding a path forward. A combination of public health infrastructure, a commitment to equity and community empowerment, and scaled-up investments will be key priorities for ensuring a necessary breakthrough in the uptake and success of these technological advancements within all countries (see table 2-3).

54. Ibid.
55. Fendos.
56. Campbell and Lee.

Table 2-3. Foundational Elements for Implementation

Public Health Infrastructure	Three characteristics determine the level of pandemic preparedness and quality of pandemic response: (1) a centralized and unified health infrastructure; (2) constant data sharing across institutions and regions, with interoperability between systems and tools for data-sharing; (3) a prioritization framework based on need and equity.
Equity and Community Empowerment	More global coordination is needed to make diagnostics, vaccines, and therapies broadly and equitably accessible. Production must be expanded globally, patent protections for vaccines amended, manufacturing recipes shared, and a standardized global framework for equitable distribution developed. Voluntary buy-in will require building community trust and empowering citizens to use information technologies in an informed, secure manner.
Financing	Financing pandemic preparedness requires rapidly scaled up domestic and international investments across countries of all income levels in order to support public health infrastructure, community empowerment, and equitable access to fast-changing technologies. One prominent estimate indicates that LMICs need to add roughly 1 percent of GDP to their domestic public spending on health and international financing needs to increase by at least US$15 billion annually, in order to avoid potential costs at least three hundred times as large.

Public Health Infrastructure

Even the wealthiest economies struggle with inadequate public health infrastructure. During the COVID-19 pandemic, problems have ranged from a lack of distributed response capacity to poor coordination and prioritization of funding, lack of equity and transparency in how resources are distributed, bureaucratic delays in disbursement, and obscurity around the needs of various stakeholders. At the outset of COVID-19, most countries lacked the appropriate health infrastructure needed to respond to the pandemic, but certain countries responded more effectively due to the crisis-centered policies and systems they built and leveraged. Whether in an LMIC or advanced economy, three main characteristics determined the initial quality of their COVID-19 response—defined as an ability to implement rapid and widespread testing, accurate contact tracing, and other government-imposed safety measures early in the pandemic.

First, a centralized and unified national health infrastructure is critical to successful outbreak response. Regular communication and coordination between public health agencies must become a definitive component of health systems globally. By reenvisioning public health as equally critical to national defense, federal entities and leaders will be more likely to provide steady support to local health departments in times of quiet and crisis. Bureaucratic processes must also be updated to better respond to emergency needs, and nations must pave a clear regulatory pathway toward supporting rapid approval of diagnostic tools, therapies, vaccines, and data technologies.[57] On a local level, academic labs, hospitals, and healthcare workers need more training and support to set up rapid and wide-scale test-and-trace campaigns, whereas communities must have their basic needs met as they engage in government-imposed safety policies, such as social distancing and imposed quarantine.

Second, constant data sharing plays a major role in any health system, and particularly pandemic response. When COVID-19 arrived, largely neglected public health agencies, local health departments, and providers across the globe were unprepared to update and sync their data systems, hindering their capacity to rapidly access, share, evaluate, and communicate information broadly.[58] In advance of the next major outbreak, data systems must be updated and standardized across regions, and public health workers and departments must be trained in their use.

Tech leaders, health officials, and political leaders must also unite in creating an interoperable ecosystem to enable different applications to not only communicate seamlessly but also integrate into one secure data repository where information can be gathered and analyzed. Similar to e-mail or SMS, users could then select the media they prefer and easily connect with others, while providing accessible information to public health leaders. For data privacy purposes, standardized guidelines around the use of any and all data must be implemented through a legally binding national, regional, or global framework. To protect individuals' privacy and prevent malicious actors from accessing sensitive citizen information from information technologies, the data repository should only be accessible to trusted healthcare agencies and decisionmakers. Individuals would then have to provide their consent before their data can be analyzed or shared, and information would be destroyed once there is no longer any use for it.

Third, a good prioritization strategy or framework is something that any public health infrastructure must perfect and continually adapt based on evolving public health needs. This becomes more feasible with ongoing data sharing, but

57. Botti-Lodovico and others.
58. Lipsitch and Grad.

also revolves around some universal principles. For example, any public crisis calls on leaders to prioritize and allocate scarce resources based on equity and need. Services to at-risk or underprivileged communities must be prioritized, as they are most often disproportionately affected by any health crisis. This may include pop-up testing centers, treatments and early vaccination, sanitation supplies, socioeconomic resources to facilitate quarantine, and so on. To successfully contain outbreaks, clinical and hypothesis-based testing needs (that is, of symptomatic patients and their contacts) must also be prioritized before significantly shifting resources to asymptomatic testing.[59] Finally, the enhanced visibility required for effective prioritization can only be achieved through ongoing coordination with local health departments and providers that directly serve communities, as well as constant data sharing to both evaluate and update the existing response strategy.

On Equity and Empowerment

All of the tools discussed above must be applied in an equitable and ethical manner, emphasizing citizen rights and empowerment. On the diagnostics front, collaborative initiatives like FIND (Foundation for Innovative New Diagnostics) have been leading efforts globally to support the development and distribution of cutting-edge diagnostic tools to LMICs. Ongoing efforts to produce more affordable rapid tests intended for surveillance could provide US$1 tests for consumption on the global market, or US$5 tests, like the FDA-approved Abbott antigen test.[60, 61] However, more collaboration is needed to expand these benefits to vulnerable populations worldwide, and facilitate broad participation by more laboratories and scientists in the development efforts.

Equity is an important consideration for countermeasures, too. Even amid a pandemic, the COVAX initiative, which manages the equitable delivery of COVID-19 vaccines, has no equal counterpart when it comes to therapies. As of November 2020, LMICs had deployed less than 2 percent of the global supply of monoclonal antibodies,[62] which are likely to become increasingly important in infectious disease mitigation over time. As new therapies are explored and optimized, the global community must work to enhance delivery of therapies to underserved communities everywhere.

Alternatively, on the vaccine front, Gavi and the Coalition for Epidemic

59. Botti-Lodovico and others.
60. Harvard T. H. Chan School of Public Health.
61. American Society of Hematology.
62. Paun.

Preparedness (CEPI)—a global collaboration convened to both facilitate vaccine development and promote equitable distribution[63]—have made considerable progress in delivering life-saving vaccines to underserved communities. Despite their efforts, however, disparities persist. For example, 20 million children across the globe lacked access to other life-saving vaccines in 2018, and competing priorities posed by COVID-19 have slowed routine vaccine delivery today.[64, 65] Once the COVID-19 vaccines were approved, wealthy countries bought out approximately 96 percent of the existing vaccine doses for COVID-19 from Pfizer-BioNTech and 100 percent of Moderna's vaccine, as well as over half of the most effective options altogether.[66,67] For many LMICs, cold chain requirements continue to thwart COVID-19 vaccine transport and delivery. As scientists build new breakthrough vaccines, research and development efforts over the next decade must also aim to enable safe delivery to remote regions everywhere.

Both now and after COVID-19 passes, the world will require a great deal of global coordination to make vaccines and therapies broadly and equitably accessible. The most critical step to achieve this is by expanding production and developing a standardized global framework for equitable distribution. The IPPPR recommends a "pre-negotiated platform" to both develop diagnostics and medical countermeasures such as vaccines and therapeutics, and ensure their quick and equitable distribution as "essential global common goods."[68] Others have urged wealthy governments such as the United States, Switzerland, and the United Kingdom to not only work to dismantle vaccine monopolies, but also cease efforts to obstruct proposals by emerging economies to amend patent protections and enable expanded manufacturing rights everywhere.[69] Vaccines, like diagnostics and treatments, are a global public good, for which monopolies are counterproductive amid a global pandemic. Pharmaceutical companies, which are getting significant governmental support, should therefore be required to not only publicly share manufacturing recipes and transfer technological know-how to manufacturers worldwide, but also work with those manufacturers to ensure vaccines are available at affordable prices for everyone.[70]

Beyond access, voluntary buy-in throughout LMICs and advanced economies alike will require increased community trust and broad empowerment.

63. Coalition for Epidemic Preparedness Innovations.
64. World Health Organization. 2019.
65. World Health Organization. 2020b.
66. Meredith.
67. Rigby.
68. Independent Panel for Pandemic Preparedness and Response.
69. Green.
70. The People's Vaccine Alliance.

Both are critical elements to the healthy functioning of any public infrastructure and particularly in outbreak prevention, as individuals play a role in stopping viral spread. Building trust and empowering individuals are duties tasked to community healthcare workers in many LMICs, but often left unfulfilled in advanced economies, where significant effort is needed to develop a real and lasting presence.

To this end, public health experts and leaders everywhere must build lasting partnerships with community health workers, local NGOs and nonprofits, tribal leaders, religious advisors, women's and minority groups, and other trusted stakeholders. These partnerships, if rooted in humility, will help build rapport with communities, identify their needs, and alleviate existing concerns over medical interventions and data privacy. International health organizations and biotechnology leaders will need to work with local and regional organizations to implement culturally and linguistically relevant information campaigns in underserved regions around the importance and safety of diagnostics, vaccines, and treatments, as well as information technologies for contact tracing and citizen reporting.

Finally, connectivity remains a hurdle to broad use of information technologies across the globe. In response, tech giant SpaceX is already planning to send 4,425 satellites to orbit in space, with the hopes of providing high-speed internet for "residential, commercial, institutional, government, and professional users worldwide."[71] As internet access expands, however, any use of information technologies should be encouraged rather than forced. Citizens should receive basic training on both their use and data privacy rights, so they are empowered to participate in outbreak response anywhere in the world.

Scaled-up Financing

The priorities described above will only be possible through a major scale-up of investments. The challenge of adequate and sustainable financing is as relevant in advanced economies as in lower-income settings. In the United States, for example, pandemic preparedness and public health were gutted by the Trump administration before COVID-19 hit. Funding cuts led the Centers for Disease Control and Prevention (CDC) to reduce their program budget for disease outbreak containment across the globe by 80 percent in 2018. Similarly, the administration collapsed the National Security Council's (NSC) "global health security" unit, stripped the U.S. Complex Crises Fund of US$30 million, and cut US$15 billion from U.S. public health spending even prior to the pandemic.[72]

71. Gibbs.
72. Sheth and Heeb.

For LMICs, initiatives like the Access to COVID-19 Tools Accelerator (ACT)—a collaboration between governments, industry, scientists, philanthropists, global health organizations, and civil society—are working to support rapid development of COVID-19 diagnostics, therapies, and vaccines, and promoting equitable access to these tools.[73] This has included commitments such as one from the Bill & Melinda Gates Foundation, in collaboration with diagnostics manufacturers such as SD Biosensor and Abbott, to pave a path toward the production of new rapid antigen diagnostic tests that cost US$5 and under.[74] However, costs of PCR tests for COVID-19 can still range from US$25 to thousands of dollars, and supply-side constraints to meeting global demand for testing and other countermeasures are persistent.[75, 76] A broader challenge is that, as of mid--2021, the ACT-Accelerator still faced a funding gap of more than US$16 billion for 2021 alone, and IMF economists have identified an incremental US$13 billion in funding needs beyond that.[77, 78] The world is not allocating adequate funding to pandemic mitigation or avoidance.

In early 2021, the G20 High Level Independent Panel convened a cross--section of global economic leaders to provide a systematic assessment of the financing required to prevent and contain future pandemics.[79] The group recommended that LMICs will need to add about 1 percent of their own GDP to public spending on health over five years, and that, as an absolute minimum, the cross-border financing will need to increase by US$15 billion per year. This is on top of complementary investments required to address issues like antimicrobial resistance, which itself requires roughly US$9 billion per year. The panel recommends an augmented global governance system involving a Global Health Threats Board, a Global Health Threats Council, and a Global Health Threats Fund, with the WHO at the center of the ecosystem. Crucially, the G20 advisory body stresses the extraordinary value of urgent action. Scaled-up investment efforts would help governments avoid budgetary costs at least three hundred times greater in future pandemics.

73. World Health Organization (n.d.).
74. World Health Organization. 2020a.
75. Markos.
76. Luthi.
77. World Health Organization. 2021a.
78. Agarwal and Gopinath.
79. G20 High Level Independent Panel on Financing the Global Commons for Pandemic Preparedness and Response.

A Call to Action

Outbreaks expose and intensify the underlying cracks in society. Issues like inequity, injustice, poverty, and food insecurity not only rise to the forefront during an outbreak or pandemic, but also worsen due to the strain on national infrastructure. The world cannot combat any sustainable development challenge without devising a plan to catch and contain infectious disease wherever it arises. COVID-19 serves as another reminder of this reality, urging nations to both invest in equitable and efficient healthcare infrastructure and empower communities to truly engage in pandemic preparedness and response.

Global pandemics highlight a truth that the public health community has known for years. No one country, region, or sector can stand on its own when it comes to fighting infectious disease. The pillars and principles proposed here are not a one-point, individual solution, but rather an integrated and collaborative approach of combining equitable and quality healthcare systems with breakthrough technologies. Together these can detect, connect, and empower communities to stop outbreaks and achieve pandemic preparedness across the globe.

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