5

Early Outbreak Detection and Control, and Prepandemic Preparedness

Brett N. Archer, Christopher T. Lee, Charles Whittaker, Victoria Y. Fan, Lee M. Hampton, Sabine L. Van Elsland, Olivier le Polain de Waroux, Olaolu M. Aderinola, Kathleen Warren, and Chikwe Ihekweazu

ABSTRACT

Infectious disease epidemics, disasters, and other public health emergencies are recurring globally with increasing frequency and complexity. Known ecological and anthropogenic drivers of epidemic risks offer opportunities to better predict hot spots and cycles of pathogen (re)emergence, deploy preventive and risk mitigation measures, enhance surveillance for early warning, and target response capacities to more effectively avert and rapidly control outbreaks before they become large and disruptive. Countries must prioritize surveillance strengthening efforts using assessments of risks, capacity, and performance before and during emergencies to build their subnational and national capacities. Moreover, investments are warranted in decision-making—by systematically strengthening surveillance and collaboration among diverse stakeholders to enhance the availability of public health intelligence for action. Such investments may be aided by incentivizing and systematically conducting independent cost analyses of surveillance systems. Ensuring the communication of timely, contextualized, and interpreted data and information to decision-makers can markedly improve the effectiveness and efficiency, and mitigate the unintended negative impacts of prevention and control measures.

INTRODUCTION

The COVID-19 (coronavirus) pandemic had a devastating impact on all societies. Analyses suggest that excess mortality ranged from two to four times reported confirmed deaths, resulting in over 28 million excess deaths during 2020–23 (Giattino et al. 2020). Estimated impacts on the global economy amount to tens of trillions of dollars (Cutler and Summers 2020; Vardavas et al. 2023;

World Bank 2022), in addition to disruptions to education and climate action as well as exacerbated levels of poverty and humanitarian needs, which disproportionately affected low- and middle-income countries (LMICs) and vulnerable communities globally.

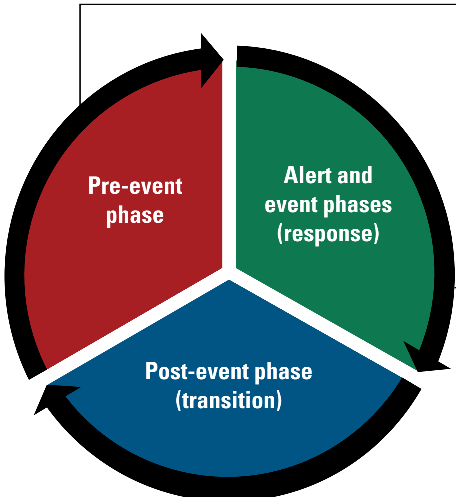
The COVID-19 pandemic, however, also resulted in many public health successes. It galvanized global actors to develop, test, and manufacture vaccines against SARS-CoV-2 in record time, which yielded an estimated US$155 billion in cost savings through infections and deaths averted by September 2021 (Yang et al. 2023). It highlighted the opportunity to leverage ongoing global changes to combat emergencies, such as increasing digital connectivity and declining genomic sequencing costs to track the emergence of SARS-CoV-2 variants, and unprecedented global sharing of sequences and other data for public health benefit (ITU 2022).[1] Moreover, it brought about a renewed programmatic focus on strengthening global public health security to become more resilient to health emergencies (WHO 2023f).

The COVID-19 pandemic should not be viewed as an isolated event. Rather, it occurred in the context of a worrying pattern of concurrent epidemics, disasters, conflicts, resource insecurity, and other major emergencies that are occurring with increasing frequency and complexity (WHO 2023c). Trends suggest a future marked by more extensive insecurity—the number of people forced to flee their homes in 2021 was double that from a decade prior (UNHCR 2023). Recent responses to outbreaks of cholera (Charnley et al. 2022) and Ebola virus disease (Jombart et al. 2020) exemplify the role conflict and insecurity play in the frequency and prolongation of emergencies. Health impacts of climate change are surging, resulting in more frequent and severe extreme weather events, accelerated spread of infectious diseases, and other tolls devastating lives and livelihoods (Romanello et al. 2023). Moreover, emergencies occur amid an increasing burden of chronic diseases that draw upon the same limited health care and public health resources. In the absence of collective and coordinated action to address these challenges, a vicious cycle of compounding impacts of concurrent public health emergencies is likely, and the strain placed on local and global resources will progressively erode the provision of adequate measures required to respond effectively to future crises, in turn intensifying their impacts. For example, disasters due to strong storms cause displacement, resulting in outbreaks among vulnerable populations, many of whom have noncommunicable diseases, leading to worse outcomes. Preparedness must be an integrated approach to address the multipronged needs.

Rapid identification and response to emerging epidemics can potentially avert localized outbreaks or prevent them from becoming global pandemics. Averting outbreaks and pandemics, and minimizing impacts when they inevitably occur, requires establishing robust and flexible collective capacities before the onset of an event. Yet investment in prevention, preparedness, early detection, response and control, and recovery, with good public health decision-making throughout, presents a paradox. That is, when these public health objectives (further explained in figure 5.1) are successfully met, the true and perceived risks associated with the epidemic are diminished, making cost savings difficult to demonstrate. This paradox presents an ongoing challenge to economies when faced with sizable costs of health emergency preparedness and competing demands. One systematic review of studies in the last two decades found that improving health emergency preparedness alone required sustained annual investments ranging from US$1.6 billion among LMICs to US$43 billion worldwide (Clarke et al. 2022). A recent World Health Organization (WHO)–World Bank estimate found that financing effective health emergency preparedness will require approximately US$30 billion per year, with a funding gap of US$10 billion per year (WHO 2023f).

This chapter outlines key considerations for strengthening early detection, control, and preparedness for epidemics, pandemics, and other emergencies. It discusses drivers of risks that may be opportunistically leveraged to inform proactive protection measures, outlines key global frameworks guiding the public health sector, and presents a case for enhanced investment in tools for decision-making to strengthen health emergency preparedness, response, and resilience.

Figure 5.1 Epidemic Phases and Associated Activity



Prevention: Activities and measures to lower existing and emerging health emergency and disaster risks.

Preparedness: Knowledge and capacities developed by governments, response and recovery organizations, communities, and individuals to effectively anticipate, respond to, and recover from the impacts of likely outbreaks or disasters.

Detection (early warning): The rapid detection of signals that may indicate potential acute public health events, which in practice forms part of an organized early warning, alert, and response mechanism of systematic detection, triage, verification (including outbreak confirmation), and communication, linked to an immediate public response.

Response: Any public health action triggered by the detection of a public health risk. May include intervention strategies targeting the following:

- Containment: Aimed at minimizing the risk of transmission from infected to noninfected individuals in order to stop an outbreak.
- Mitigation: Aimed at slowing the disease and reducing morbidity and mortality and associated demand on health care resources.

Recovery: The restoring or improving of livelihoods and health, as well as economic, physical, social, cultural, and environmental assets, systems, and activities, of an emergency-affected community or society, aligning with the principles of sustainable development and build back better, to reduce disaster and outbreak risks.

Sources: Adapted from OECD 2020 and WHO 2020.

UNDERSTANDING DRIVERS OF EPIDEMIC AND PANDEMIC RISK TO PREDICT RISK AND STRENGTHEN SURVEILLANCE

The public health risk related to infectious disease outbreaks is a function of the characteristics of the pathogen (severity and potential for spread), the probability of exposure, and the context in which they emerge—particularly the vulnerability of the population and the local public health response capacity (Poljanšek et al. 2018). The public health risk from an epidemic often increases with the presence of other hazards because of a combination of overstretched response capacities and increased population vulnerability. This section highlights an exemplary subset of ecological and anthropogenic drivers of pandemic risk, and it demonstrates how our scientific understanding of the impact of these drivers offers opportunities for improvements to public health surveillance and response.

First, among other impacts on health, global climate change intensifies zoonotic risk through changes in the ecology of animal reservoir hosts and vector populations (Thomson and Stanberry 2022), further increasing the frequency of cross-species virus transmission in a growing number of geographic regions (Carlson et al. 2022). Studies have underscored the intricate relationships between climatic dynamics—such as seasonal variations in temperature and precipitation, or larger-scale climatic phenomena like El Niño—in the emergence and spread of Lassa fever, Rift Valley fever, or cholera, for example (Jutla et al. 2013; Redding et al. 2017; Redding et al. 2021). Moreover, land use changes (for example, deforestation and urbanization) may increase the proximity between humans and potential or known environmental reservoirs of infectious diseases, and the risk of spillover (cross-species) transmission events (Gibb et al. 2020; McKee et al. 2021; Redding et al. 2019).

Understanding these risks, and how they drive epidemics, can lead to more targeted and anticipatory approaches to disease surveillance and forecasting, better define risk and potential hot spots based on proxy variables, and better target surveillance and prevention activities in the most vulnerable areas and communities. Examples include adoption of climate models to predict and enhance early warning for zoonotic and vector-borne diseases (Caldwell et al. 2021; Lotto Batista et al. 2023), as well as the use of animal populations as sentinel surveillance systems for diseases like West Nile virus (Gossner et al. 2017).

Second, the increasingly interconnected world facilitates the spread of infectious diseases (Tatem, Rogers, and Hay 2006). Urbanization and population movement amplify epidemic risk of certain pathogens and the potential for rapid global dissemination of pathogens. During the COVID-19 pandemic, population density was a significant driver of transmission intensity (Rader et al. 2020). As such, population mobility data (for example, from air traffic, cell phone usage, and traveler screening) provide opportunities for innovative, data-driven approaches to improve epidemic risk prediction, such as predicting risks posed by a local event on other geographic regions, monitoring the importation of novel SARS-CoV-2 variants, or reconstructing transmission dynamics in settings with otherwise limited surveillance (Chang et al. 2021; Kahn et al. 2019; Kucharski et al. 2023; Oliver et al. 2020; Sharma et al. 2023).

Third, the contexts created by humanitarian crises often amplify epidemic risks. Examples include factors that increase risk of pathogen emergence and transmission (for example, high population density, poor shelters and sanitation, and disruptions to routine vaccinations or vector control), and severity (for example, due to underlying malnutrition or limited access to treatment) (Jones et al. 2008). In the Republic of Yemen, for example, conflict, destruction of infrastructure (such as health, water, or sanitation), chronic malnutrition, displacement, and overcrowding, among other factors, have fueled the largest cholera outbreak in recorded history (Federspiel and Ali 2018). As such, ensuring adequate epidemic surveillance and response in humanitarian settings is paramount to reduce the risk of excess mortality and morbidity in already fragile populations, and beyond. These measures include the development of community-based early warning systems (Kongelf et al. 2016; Ratnayake et al. 2020), supported by agile digital solutions of reporting and monitoring—for instance, WHO's Early Warning Alert and Response System to establish surveillance and response activities in difficult and remote settings without reliable internet and electricity.

Fourth, immunity gaps increase the risk of vaccine-preventable disease outbreaks (Abubakar et al. 2019; Dureab et al. 2019). Monitoring of vaccination coverage and key influences on vaccine uptake (for example, sociocultural factors and a population's ability to access vaccines) is essential not only to improve routine vaccine coverage but also to understand and predict epidemic risks and mobilize strategies and resources for prevention and mitigation. Capturing data at the local level is important because, even in highly vaccinated settings, epidemics of vaccine-preventable diseases are often driven by local clusters of unvaccinated individuals (Masters et al. 2020).

These risks frequently compound. For example, humanitarian crises often exacerbate the risk of measles outbreaks and other vaccine-preventable diseases such as diphtheria by creating immunity gaps (Lam, McCarthy, and Brennan 2015). Disruptions to routine health services during conflict and displacement often result in suboptimal vaccination coverage, and conditions such as overcrowding, poor sanitation, and malnutrition enhance transmission and severity. This susceptibility is further complicated by limited health care infrastructure in crises, with limited surveillance, delayed case detection, and insufficient response capacities potentially leading to higher-than-typical morbidity and mortality (Kouadio, Kamigaki, and Oshitani 2010).

In contexts of past and ongoing outbreaks and limited historical data, serological surveillance or surveys are useful tools to better understand population immunity profiles and associated factors (such as community trust in vaccines), enhance risk prediction, and inform targeted interventions. For example, serological surveillance has been used throughout COVID-19 to predict the size of peaks driven by a novel variant (Buss et al. 2022) as well as to inform relaxation of imposed control measures (Kraay et al. 2021).

FRAMEWORKS FOR STRENGTHENING GLOBAL HEALTH SECURITY

The International Health Regulations (IHR) have formed a normative basis for global health security implementation since their introduction in 1969. They provide a legally binding agreement among 196 countries to develop, maintain, and monitor implementation of capacities to prevent, detect, and respond to public health threats, as well as to report these events to WHO (WHO 2016). Born out of response to deadly epidemics, the IHR have undergone numerous revisions prompted by increasing risks of disease (re)emergence with international travel and trade, as well as global events such as the SARS (severe acute respiratory syndrome) epidemic in 2003 and, most recently, the COVID-19 pandemic.

The IHR further require State Parties' self-assessment annual reporting, with reports supplemented by tools including Joint External Evaluations, simulation exercises, after-action reviews, and independent measures (for example, the Global Health Security Index), all geared toward assessing country-level preparedness and informing strategies to develop capacity and improve compliance with the IHR. The COVID-19 pandemic, however, highlighted limitations of these accountability mechanisms, which primarily rely on static capacity measures rather than evaluating the functionality of systems under real-world conditions. Research investigating the correlation between preparedness measures and actual population health outcomes has yielded inconsistent results, which may partly be attributed to the sensitivities in model parameters applied and the inherent unpredictability of factors, such as sociopolitical influences, that affect the translation of preparations into a robust response during an emergency (Bollyky et al. 2022; Ledesma et al. 2023; NTI and Johns Hopkins Center for Health Security 2021; Nuzzo and Ledesma 2023). One study found that higher Joint External Evaluations scores were associated with significantly fewer overall communicable disease deaths, but not fewer COVID-19 deaths (Jain et al. 2022).

Despite their importance as a tool to help countries develop capacity-building plans, and despite their revisions during the COVID-19 pandemic, the Joint External Evaluations are not designed to predict future performance in pandemics. Such static measures of capacity provide only one dimension for informing risk assessments. As outlined in the previous section, other highly variable dynamics of risk include the hazard, probability of exposure, and, perhaps most dynamically, vulnerability of individuals, communities, systems, and assets. The triangulation of data across these dynamics provides the means for informing investments to best tackle recurring threats such as pandemics through not only boosting systems' capacities but also reducing population vulnerabilities and exposures to hazards.

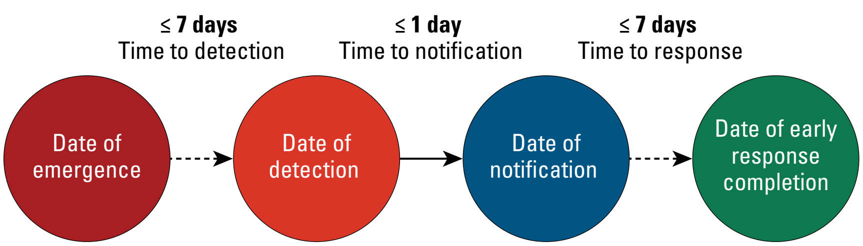
Accountability challenges persist for ensuring the timeliness of detection and response. Because of the difficulty in generating counterfactual data on epidemics averted, evaluating the effectiveness of surveillance systems and investigations is challenged by a lack of clear outcome measures. In this context, there has been an increased focus on the promise of timeliness metrics, indicating rapid detection and response to emerging threats as a performance metric of public health surveillance systems, as well as a quality improvement framework (Frieden et al. 2021).

The "7-1-7" target, shown in figure 5.2 and used increasingly to assess country performance in real-world conditions, identifies bottlenecks to rapid detection, notification, and early response (Bochner et al. 2023). Using this approach, countries have begun to use systems analyses for outbreaks that were successfully contained and to identify bottlenecks for larger events to inform systems improvement. As opposed to the aforementioned regulatory performance assessments, the 7-1-7 target can be integrated into functional assessments or "early action reviews" to align stakeholders during the emergence of outbreaks, and to inform targeted measures to prevent and mitigate the impacts of new epidemics and pandemics (Mayigane, Vedrasco, and Chungong 2023). Similarly, after-action reviews have demonstrated potential to assess the what, how, and why of a response to real-world events; identify best practices and challenges encountered; and propose mid- and long-term actions for improvement.

The Independent Panel for Pandemic Preparedness and Response and the IHR Review Committees stressed the importance of new assessments and tools that assess operational capacities in real-world stress situations (IPPPR 2023).[2] Furthermore, numerous independent performance assessments emphasize the need for more predictable and sustainable financing at the international and national levels, as well as stronger frameworks to address international cooperation (WHO 2021b).[3] Notable steps made toward these goals include the launch and ongoing implementation of a framework for strengthening health emergency prevention, preparedness, response, and resilience (HEPR). The HEPR framework addresses governance, systems, and financing issues noted during the COVID-19 pandemic, and offers prioritized solutions (WHO 2023f). Although HEPR addresses all hazards, the solutions proposed are echoed in disease-specific preparedness and surveillance strategies, including current implementation plans for the Pandemic Influenza Preparedness Framework and the associated Global Influenza Surveillance and Response System (WHO 2023e).

Success of these initiatives, however, depends on overcoming numerous challenges. These challenges include delivering and sustaining increased domestic financing to achieve goals set out under national action and investment plans, ensuring stronger alignment of international financing to support national aspirations more synergistically and equitably, and addressing financing mechanisms to improve the scale and speed to access finances for the deployment of large-scale operations and medical countermeasures during emergencies (refer to the policy considerations section later in this chapter).

Figure 5.2 The 7-1-7 Timeliness Metrics and Targets for Detection, Notification, and Response Related to Public Health Events



Source: WHO 2023d.

INVESTMENT IN TIMELY PUBLIC HEALTH DECISION-MAKING

Substantial data show the health and economic benefits of public health interventions during emergencies (Juneau et al. 2022). The availability of data and information before and during an epidemic can markedly improve the efficiency of prevention, preparedness, and control efforts by informing the choice, timing, targeting, and impact monitoring of interventions, among other benefits. For example, many diseases can cause acute watery diarrhea clinically indistinguishable from that caused by cholera, but the appropriate application of surveillance and diagnostic tests can enable targeting of cholera-specific vaccinations, leading to sizable cost savings (Hampton, Johnson, and Berkley 2022; Lee et al. 2019; Xu et al. 2024).

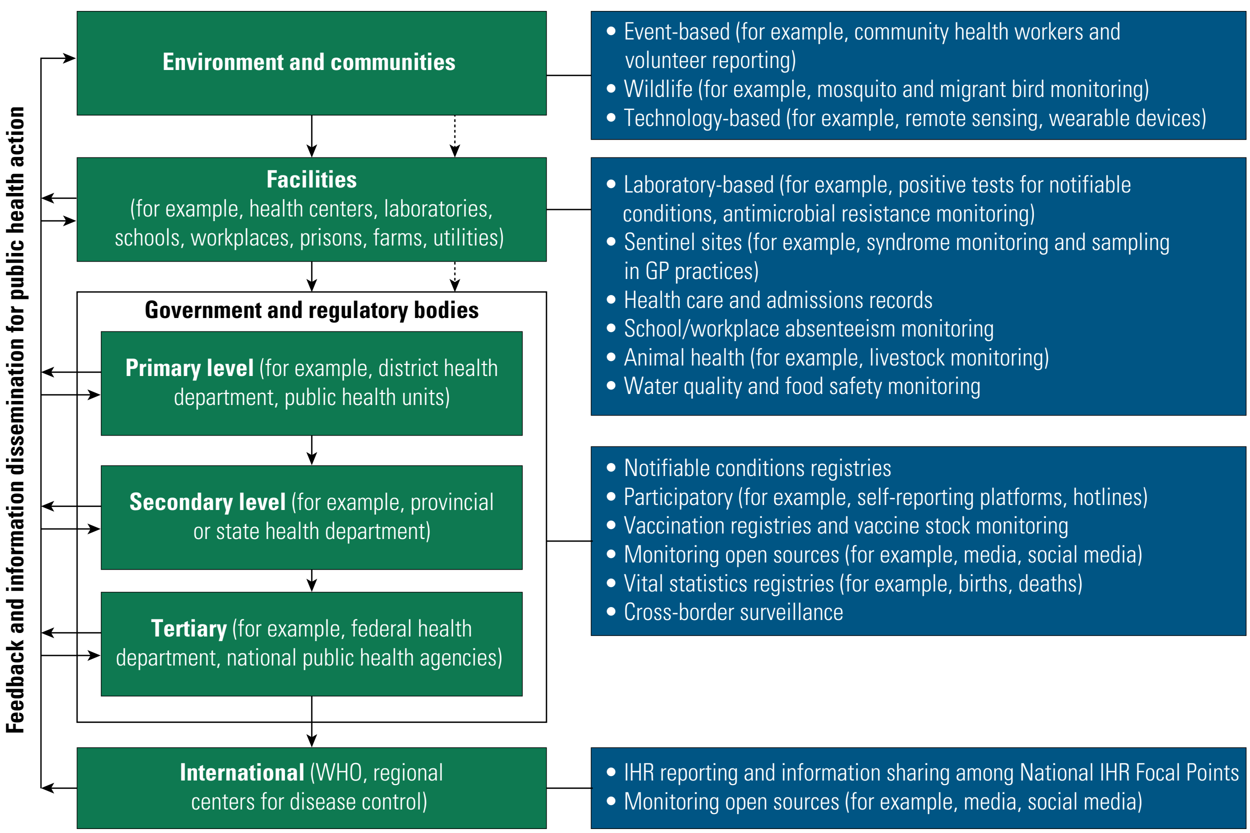
It is also well established that timely detection of outbreaks can allow more effective and efficient implementation of measures to contain an outbreak compared to delayed detection and the ensuing costly response. For example, of 12 Ebola virus disease outbreaks detected during 2013–22, the 9 outbreaks confirmed within 33 days were contained to less than 150 cases each. In contrast, the 2013–16 West Africa outbreak, confirmed 110 days after its start, caused 28,610 reported cases and cost international donors alone at least US$1.8 billion. The 2018–20 outbreak predominantly in eastern provinces of the Democratic Republic of Congo was confirmed 93 days after its start, caused 3,470 reported cases, and committed funding from international donors ranging from US$730 million to US$1.18 billion (Hampton et al. 2023; Zeng et al. 2023).

A recurring example is the identification and response to novel influenza subtypes in animals, resulting in an interruption of transmission among the animal population before the first human cases have been detected (Lee et al. 2017). Moreover, outbreaks of Rift Valley fever have demonstrated the value of intersectoral information sharing and response to zooneses, with early detections in animal populations providing an opportunity for preventive interventions, enhanced clinical care, and timely response to mitigate human infections (Archer et al. 2013). Such events exemplify the critical need to apply a One Health approach in identifying and responding to disease threats in people, animals, and plants, with international calls to integrate or interconnect systems and responses, and institutionalize a collaborative effort to disease control (Hayman et al. 2023; WHO 2023b).

A key remaining challenge is the generation and provision of timely and adequate information to appropriate decision-makers to prevent infectious disease outbreaks from becoming catastrophic events (Lipsitch and Santillana 2019; Tan 2006). Adequately answering the diverse array of questions that arise—both in routine monitoring of prioritized public health hazards and risks and throughout the course of an epidemic—requires a range of data. On a routine basis, surveillance supports, for example, monitoring and assessment of endemic disease trends, health care and preventive service provision and resource use, and aberration detection for events of potential clinical or public health importance. Countries typically achieve these aims by deploying a variable array of surveillance methods designed to generate data on the occurrence of a health-related event within human and animal populations, as well as the environment around them, through established systems and chains of communication, coupled with secondary analyses of administrative and other existing data (figure 5.3).

At the onset of an epidemic, when containment is most feasible and cost-effective, the deployment of the most appropriate set of interventions depends on sufficient insights into the causative pathogen and its epidemiological characteristics; the burden and spread within the affected population, and associated health and socioeconomic impacts; an understanding of community enablers of (or barriers to) effective epidemic control; and any major uncertainties across these variables. As the epidemic progresses, there is a need to continuously monitor for major changes in these and other parameters, to assess the impacts of interventions to adjust and better target control strategies, and to continuously right-size these strategies to maximize their impact while minimizing adverse effects on individuals and societies.

Figure 5.3 Simplified Diagram of Data and Information Flow in Public Health Surveillance Systems

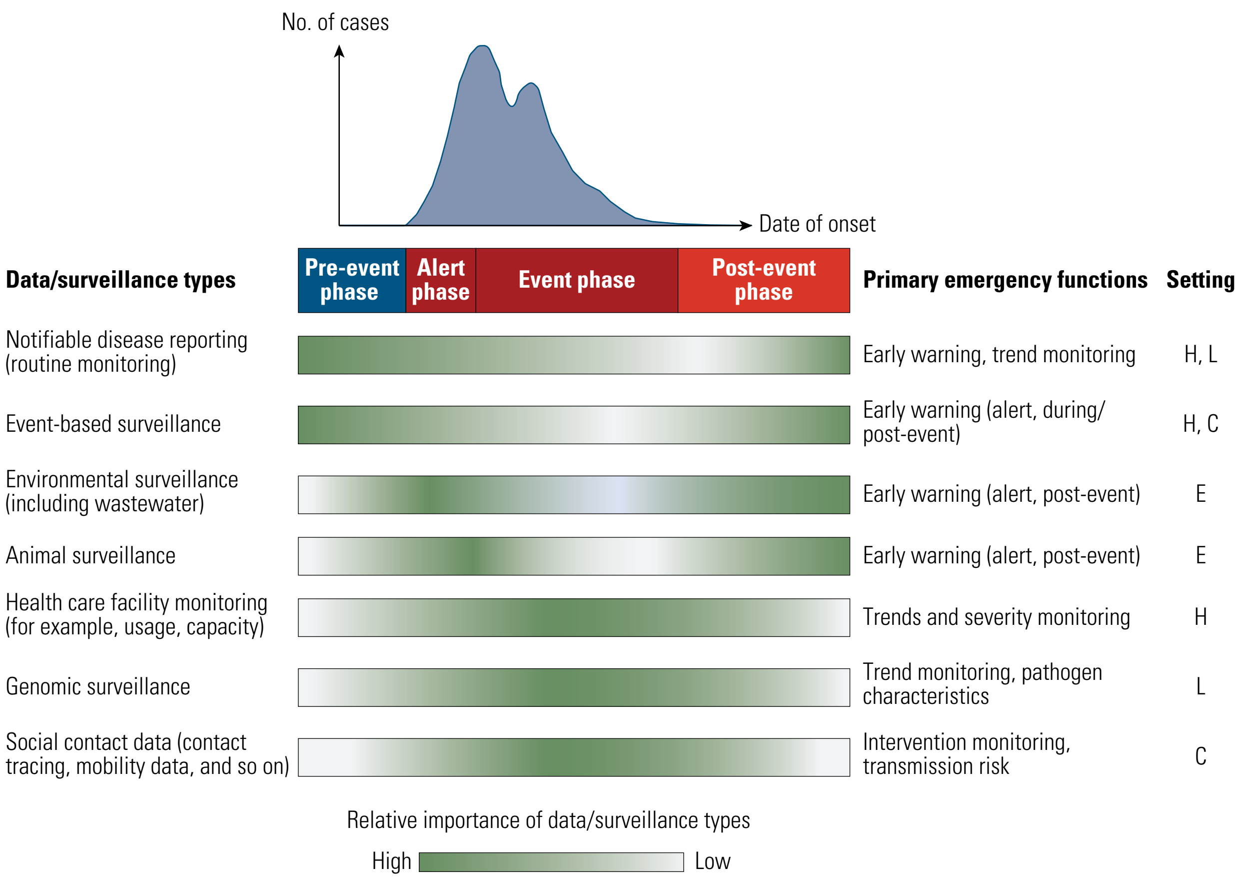


Source: Original figure for this publication.

Note: GP = general practitioner; IHR = International Health Regulations; WHO = World Health Organization.

National and subnational governments are primarily responsible for establishing and managing a suite of surveillance systems to address these diverse information needs while generating or digesting information from other sources (for example, special studies, outbreak investigations, and research) to fill information gaps. In the public health sector, this responsibility typically rests with ministries or departments of health that are variably supported by national public health agencies, other government sectors, academia, nongovernmental and civil society organizations, public and philanthropic funders, foreign governments, and regional and international organizations and agencies. These authorities and partners must collectively operate and flexibly apply a wide range of surveillance systems to address evolving information needs during and outside of public health emergencies (figure 5.4).

Figure 5.4 Variability and Relative Importance of Different Data and Surveillance Types for Meeting Emergency Preparedness and Response Objectives over the Course of an Epidemic



Source: Original figure created for this report.

Note: Data/surveillance types listed are illustrative and nonexhaustive; many other approaches typically exist in countries. The assigned relative importance, primary functions, and settings relate to the outputs and decision themes that each surveillance type may be best placed to inform in or around an epidemic. Surveillance serves many other primary and complementary objectives for both routine monitoring and emergency response, and their relative importance in any given phase is highly variable across different pathogens and contexts. C = community; E = environment; H = health facilities, L = laboratories.

At face value, the task of collecting, analyzing, and interpreting data from multiple sources, and communicating health intelligence, appears simple. In most countries, however, public health surveillance comprises a complex array of systems that have evolved organically over many decades. Health authorities must contend with fragmented and sometimes duplicative and inflexible systems, often characterized by independent silos of unlinked activity across administrative levels, diseases, sectors, and organizations, with most funding earmarked to deliver against a narrow set of surveillance objectives for specific diseases (Choi 2012).

Addressing systems' fragmentation is critical for improving the timeliness and robustness of information available to inform early outbreak detection and control. For over 20 years, strategies for Integrated Disease Surveillance and Response (IDSR) have been prioritized internationally and have demonstrated mixed successes in LMICs (Mremi et al. 2021). The COVID-19 pandemic brought renewed attention to the need to specifically enhance collaboration across the surveillance landscape to address diverse decision-maker needs—termed "collaborative surveillance" (WHO 2023b). The collaborative surveillance approach encompasses prioritizing One Health systems to more cohesively address drivers of disease emergence and surveillance opportunities at the human-animal-environment interface (Hayman et al. 2023). The degree of local application of these global strategies is also context-dependent, and local human, animal, and environmental health authorities must ultimately choose the suite of surveillance approaches and capacities that best address decision-making needs in their local context.

Beyond the specific technical and contextual considerations, domestic financing and international investor interests heavily shape the ultimate design of a country's surveillance systems. Moreover, a tendency exists for individual surveillance systems to overstate their utility and attract investment in limited objectives without considering opportunity costs to other systems, and risking data gaps to address this and other critical surveillance objectives. This practice can result in a lack of (or, worse, misleading) information for making decisions and taking actions at different phases of emergencies. This chapter, therefore, stresses the need for a more holistic outlook on the impacts of investments in surveillance capacities and offers several considerations for strategic improvement (box 5.1).

Surveillance is incomplete without coordinated, multisectoral public health action. Public health emergency operation centers serve as a crucial hub for information exchange and resource coordination (WHO 2015). The establishment of these centers at both national and subnational levels facilitates the timely triangulation and use of data from various sources, interconnected with response mechanisms (Balajee et al. 2017; Oyebanji et al. 2021). However, numerous countries face challenges in fully operationalizing such centers, in part because of a disproportionate focus on physical infrastructure, often at the expense of other vital investments such as the development of robust legal and governance frameworks (Elmahal et al. 2022).

Box 5.1

Consideration for Critical Design and Appraisal of Surveillance Investments

- **Define use cases and work backward.** Addressing this full range of informational needs requires an appropriate mosaic of surveillance approaches, with strong coordination and collaboration between systems and their curators. This desired mosaic of many data sources must, however, be balanced against the resource requirements and overheads inherent in maintaining and coordinating across multiple surveillance workflows; accordingly, it requires prioritization and organizational design of surveillance to maximize both impact potential and efficiency. Strategic investments in systems thinking approaches carry the potential to improve overall utility in informing public health decisions and action, for example, by defining data use cases (decision-making objectives) and mapping upstream data best suited to deliver against each use case.
- **Systematically evaluate decision-making and action potential of the system.** The value of public health data lies in their ability to inform impactful decisions and prompt action. The usefulness of collecting specific information depends on the costs and benefits of each option, the relevance of the data to the decision at hand, and how often that decision arises. Decision analysis, widely used to assess the cost-effectiveness in health care, can also be applied to assess surveillance systems, guide outbreak response decisions, and prioritize among different options for investing in improving information available for decision-making.
- **Assess robustness of downstream capacities to effectively use surveillance outputs.** Surveillance must be coupled with the necessary public health intelligence capacities (skilled workforce, established systems and infrastructure, standardized processes, connectivity, and so on) to collate, verify, analyze, contextualize, and interpret information triangulated from multiple health and nonhealth sources; undertake systematic assessments of evolving risks; and effectively communicate findings with relevant response authorities. Efforts to strengthen data collection and technologies for event detection, and to enhance collaboration capacity, will be in vain if not met with an adequately trained workforce and established processes to transform data into actionable intelligence.
- **Prioritize core, routine systems with the flexibility to address multiple hazards and to surge during emergencies.** Attributes inherent in any chosen surveillance approach should inform investments in core or recommended approaches. Other approaches may serve to enhance surveillance when resources allow but should be considered secondary to ensuring the optimization of core surveillance functions. These systems should have flexibility to address multiple, diverse hazards (pathogens and other threats) and surge during emergencies. Such systems and capacities require long-term investments to become a core resource at every level of public health delivery and decrease reliance on contingency surveillance tools introduced midevent.
- **Review the sufficiency of evidence on new surveillance technologies before scaling.** Although investments in emerging technologies offer attractive opportunities to augment surveillance capacities, their introduction must be carefully curated. For example, wastewater and genomic surveillance, coupled with either targeted or pathogen-agnostic laboratory investigations, have the potential for more detection of (re)emerging pathogens. Likewise, digital technologies (such as mobile applications, location tracking, and wearables) have the potential to augment traditional data collection. However, investments must be balanced against core systems while assessing how best to equitably operationalize these technologies in diverse contexts and evaluate the utility and cost-benefit of data generated relative to other approaches.

Given the importance of timely decision-making and action in dealing with outbreak-prone diseases, investments can help ensure that public health decision-making is well structured, and individuals in decision-making positions are competent to make decisions and plans. Notably, because of the fast-evolving nature of outbreaks, decisions and actions must proceed amid a degree of uncertainty. Delays due to indecision—for example, regarding implementation of outbreak responses or requests for outside assistance with responses—can lead to severe negative consequences in outbreak-affected communities (Hassan et al. 2018). Devolving decision-making to the lowest possible level can help address such issues, as can deliberate building and maintaining of relationships and processes among institutions involved with decisions and their implementation, such as scientific advisory groups, government ministries, and international organizations.

POLICY CONSIDERATIONS FOR UNDERSTANDING THE VALUE OF SURVEILLANCE

Amid a paucity of research and evidence on the cost-effectiveness and value of surveillance, there is a need for global-level investment in understanding both the relative value of individual surveillance approaches and the value of public health surveillance overall. Recent research highlights that very few economic evaluations of infectious disease surveillance systems have been performed (De Vries et al. 2021). When economic evaluations have been undertaken, they have overwhelmingly focused on surveillance systems for individual pathogens (Herida, Dervaux, and Desenclos 2016).

Multiple factors complicate economic evaluations of surveillance systems. First, these evaluations must consider the fact that surveillance systems operate as part of a package of tools. In other words, because disease surveillance's value lies in improving use of medical and nonpharmaceutical interventions at a population level, the potential impact of surveillance must reflect and is limited by the potential impact of those interventions. However, economic evaluations of surveillance are still possible through comparisons of carefully constructed counterfactuals on what would happen with the use of medical and nonpharmaceutical interventions in the presence versus the absence of disease surveillance (WHO 2005). Especially for diseases that can cause socially and economically disruptive outbreaks, such evaluations should incorporate a social perspective.

Second, surveillance systems can potentially collect information on a range of diseases, with synergies across diseases for many of the system components. For example, a given surveillance worker with the right training can potentially identify and report suspected cases of many diseases. Economic evaluations of surveillance systems should ideally reflect the synergies from tracking multiple diseases with a single system despite the increased challenges of assessing the value and costs of surveillance for multiple diseases instead of a single disease. Such joint surveillance can have potentially large economies of scope—that is, for multiple diseases rather than for a single disease.

Third, surveillance systems can address both diseases that occur relatively frequently, such as measles and cholera, and diseases that occur more rarely, such as novel zoonotic diseases like COVID-19. Surveillance systems can potentially have great value in guiding control measures for both relatively frequent and rare diseases, including triggering timely responses to and containment of novel zoonotic outbreaks, which can be devastating if not contained. However, data on the frequency and consequences of rare diseases and the potential impact of surveillance systems in their control can be relatively sparse. Nevertheless, economic evaluations of surveillance systems should ideally capture the value and costs of their addressing both frequent and rare diseases.

Despite these challenges, economic evaluations can be useful for assessing the value of surveillance and delineating what constitutes a menu of "best buys" for surveillance (Fan et al. 2023). One key lesson from efforts to control human immunodeficiency virus and acquired immune deficiency syndrome (HIV/AIDS), tuberculosis, and malaria is the role and importance of expanding the measurement of costs and benefits of disease control efforts, including surveillance of these diseases, and either vertical systems (for a specific disease) or horizontal systems (for multiple diseases). Economic evaluations can provide assessments of previous investments and guide future investment decisions, perhaps most saliently demonstrated in the case of HIV/AIDS and the US President's Emergency Plan for AIDS Relief (Ruiz 2023). In another example, an evaluation conducted in Burkina Faso with a focus on meningitis outcomes found that the implementation of IDSR had a low cost (US$$0.01 per capita) yet was associated with statistically significant reductions in meningitis incidence and mortality and potentially with cost savings (Somda et al. 2010). Given the paucity of economic evaluations of surveillance systems, qualitative assessments of such systems' value, potentially relying on gray literature or the experience of practitioners and public health authorities, can be useful, but rigorous and quantitative independent assessments are preferable whenever possible.

CONCLUSIONS

The concurrent occurrence of epidemics, natural disasters, humanitarian crises, conflicts, and other emergencies is an everyday reality faced by communities the world over. Further, the continued emergence of pathogens with pandemic potential is a certainty. The cost of indecision and inaction, or delayed and ill-informed actions, is great. Concerted efforts, however, can prevent or greatly mitigate the tremendous impacts of these events on public health and society.

The IHR and WHO's HEPR framework underscore the need to strengthen national and local health systems to achieve global health security. Among the top priorities advocated is the need to strengthen surveillance capacity and collaboration among stakeholders to improve public health decisions. A premise of enhancing local (subnational) insights of evolving risks, applied to inform local decisions and local action, must be at the forefront of capacity development investments and activities. Moreover, the growing global knowledge base of the drivers of epidemic and pandemic risks can be operationalized to better target surveillance and preparedness efforts.

Delivering the diverse and evolving information required for decision-making in both "peace time" and before, during, and after public health emergencies will require a careful selection and organization of a suite of surveillance approaches, interconnected with response capacities. The investment design and appraisal considerations outlined in this chapter can support counteracting some of the inherent fragmentation in surveillance systems.

There remains a pressing need to strengthen the evidence base to support best investments in decision-making capacities. Such strengthening should include systematic and independent evaluations of the effectiveness and cost-effectiveness of surveillance approaches, and the value of surveillance overall. High-quality research is vital for enhancing pandemic and epidemic intelligence, forming the basis for effective collaborative surveillance and informed public health decisions, which should consider internationally prioritized themes, such as the application of technologies (for example, artificial intelligence) and multisectoral approaches (WHO 2024).

The COVID-19 pandemic served as a stark reminder of the profound impact that communicable diseases can have on societies worldwide. It was, however, neither the final pandemic we will face nor an isolated incident—in fact, health emergencies are a daily reality. By strategically investing in the preparation of our health systems and unlocking the potential to generate and act on health intelligence at all levels, we can preempt epidemics and pandemics before they take hold, enable the early detection of emerging risks, and guide targeted response interventions to prevent localized outbreaks from escalating into full-blown catastrophes.

ANNEX 5A. GLOSSARY

Global public health security: The activities required, both proactive and reactive, to minimize the danger and impact of acute public health events that endanger people's health across geographical regions and international boundaries (WHO 2020).

Hazard: A process, phenomenon, or human activity that may cause loss of life, injury, or other health impacts; property damage; social and economic disruption; or environmental degradation (WHO 2020). Hazards may be single, sequential, or combined in their origin and effects, and, under the WHO classification of hazards, include natural hazards (biological, extraterrestrial, geophysical, and hydro-meteorological), human-induced hazards (technological and societal), and environmental hazards (environmental degradation).[4]

One Health: An integrated, unifying approach that aims to sustainably balance and optimize the health of humans, animals, plants, and ecosystems. It recognizes the close link and interdependence among the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems). The approach mobilizes multiple sectors, disciplines, and communities at different levels of society to work together to foster well-being and tackle threats to health and ecosystems while addressing the collective need for clean water, energy, and air and safe and nutritious food; taking action on climate change; and contributing to sustainable development (FAO et al. 2022).

Public health intelligence: A core public health function responsible for identifying, collecting, connecting, synthesizing, analyzing, assessing, interpreting, and generating a wide range of information for actionable insights and disseminating these insights for informed and effective decision-making to protect and improve the health of populations.[5]

Risk: The potential loss of life, injury, or destroyed or damaged assets that could occur to a system, society, or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability, and capacity (UN 2016; WHO 2020).

Surveillance (public health surveillance): The systematic, ongoing collection, collation, and analysis of data for public health purposes and the timely dissemination of public health information for assessment and public health response, as necessary (WHO 2016, 2020).

Threat: A person, place, thing, or development, or a combination of these elements, that can harm health security, either as a real or perceived danger (WHO 2014). Examples include antimicrobial resistance or environmental threats such as climate change. Threats can also refer to deliberate events such as an intent to release a hazardous substance to cause harm. Refer also to the definition of hazard.

Vulnerability: The characteristics and circumstances (physical, social, economic, and environmental factors or processes) of an individual, community, system, or asset that make it susceptible to the effects of a hazard (UN 2016; WHO 2021a).

NOTES

Disclaimer: The findings and conclusions in this chapter are those of the authors and do not necessarily represent the official position of the organizations for which they work.

1. Refer also to National Human Genome Research Institute, "DNA Sequencing Costs: Data," https://www.genome.gov/about-genomics/fact-sheets/DNA-Sequencing-Costs-Data.
2. Refer also to WHO, "IHR Review Committees," https://www.who.int/teams/ihr/ihr-review-committees.
3. Refer also to WHO, "WHO Dashboard of COVID-19 Related Recommendations," http://bit.ly/3MGMq3o.
4. United Nations Office for Disaster Risk Reduction, "Definition: Hazard" (accessed April 14, 2023), https://www.undrr.org/terminology/hazard.
5. United Nations Department for General Assembly and Conference Management, "UNTERM: The United Nations Terminology Database," (accessed April 14, 2023), https://unterm.un.org/unterm2/en/.

REFERENCES

Abubakar, Ahmed, Mahmud Dalhat, Abdulaziz Mohammed, Olayinka Stephen Ilesanmi, Uchenna Anebonam, Nyampa Barau, Sarafadeen Salami, et al. 2019. "Outbreak of Suspected Pertussis in Kaltungo, Gombe State, Northern Nigeria, 2015: The Role of Sub-Optimum Routine Immunization Coverage." *Pan African Medical Journal* 32 (Suppl 1): 9. https://doi.org/10.11604/pamj.supp.2019.32.1.13352.

Archer, Brett N., Juno Thomas, Jacqueline Weyer, Ayanda Cengimbo, Dadja E. Landoh, Charlene Jacobs, Sindile Ntuli, et al. 2013. "Epidemiologic Investigations into Outbreaks of Rift Valley Fever in Humans, South Africa, 2008–2011." *Emerging Infectious Diseases* 19 (12). https://doi.org/10.3201/eid1912.121527.

Balajee, S. Arunmozhi, Omer G. Pasi, Alain Georges M. Etoundi, Peter Rzeszotarski, Trang T. Do, Ian Hennessee, Sharifa Merali, et al. 2017. "Sustainable Model for Public Health Emergency Operations Centers for Global Settings." *Emerging Infectious Diseases* 23 (13). https://doi.org/10.3201/eid2313.170435.

Bochner, Aaron F., Issa Makumbi, Olaolu Aderinola, Aschalew Abayneh, Ralph Jetoh, Rahel L. Yemanaberhan, Jenom S. Danjuma, et al. 2023. "Implementation of the 7-1-7 Target for Detection, Notification, and Response to Public Health Threats in Five Countries: A Retrospective, Observational Study." *The Lancet Global Health* 11 (6): E871–79. https://doi.org/10.1016/S2214-109X(23)00133-X.

Bohl, Jennifer A., Sreyngim Lay, Sophana Chea, Vida Ahyong, Daniel M. Parker, Shannon Gallagher, Jonathan Fintzi, et al. 2022. "Discovering Disease-Causing Pathogens in Resource-Scarce Southeast Asia Using a Global Metagenomic Pathogen Monitoring System." *Proceedings of the National Academy of Sciences* 119 (11): e2115285119. https://doi.org/10.1073/pnas.2115285119.

Bollyky, Thomas J., Erin N. Hulland, Ryan M. Barber, James K. Collins, Samantha Kiernan, Mark Moses, David M. Pigott, et al. 2022. "Pandemic Preparedness and COVID-19: An Exploratory Analysis of Infection and Fatality Rates, and Contextual Factors Associated with Preparedness in 177 Countries, from Jan 1, 2020, to Sept 30, 2021." *The Lancet* 399 (10334): 1489–512. https://doi.org/10.1016/S0140-6736(22)00172-6.

Buss, Lewis, Carlos A. Prete, Charles Whittaker, Tassila Salomon, Marcio K. Oikawa, Rafael H. M. Pereira, Isabel C. G. Moura, et al. 2022. "Predicting SARS-CoV-2 Variant Spread in a Completely Seropositive Population Using Semi-Quantitative Antibody Measurements in Blood Donors." *Vaccines* 10 (9): 1437. https://doi.org/10.3390/vaccines10091437.

Caldwell, Jamie M., A. Desiree LaBeaud, Eric F. Lambin, Anna M. Stewart-Ibarra, Bryson A. Ndenga, Francis M. Mutuku, Amy R. Krystosik, et al. 2021. "Climate Predicts Geographic and Temporal Variation in Mosquito-Borne Disease Dynamics on Two Continents." *Nature Communications* 12 (1): 1233. https://doi.org/10.1038/s41467-021-21496-7.

Carlson, Colin J., Gregory F. Albery, Cory Merow, Christopher H. Trisos, Casey M. Zipfel, Evan A. Eskew, Kevin J. Olival, et al. 2022. "Climate Change Increases Cross-Species Viral Transmission Risk." *Nature* 607 (7919): 555–62. https://doi.org/10.1038/s41586-022-04788-w.

Chang, Serina, Emma Pierson, Pang Wei Koh, Jaline Gerardin, Beth Redbird, David Grusky, and Jure Leskovec. 2021. "Mobility Network Models of COVID-19 Explain Inequities and Inform Reopening." *Nature* 589 (7840): 82–87. https://doi.org/10.1038/s41586-020-2923-3.

Charnley, Gina E. C., Kévin Jean, Ilan Kelman, Katy A. M. Gaythorpe, and Kris A. Murray. 2022. "Association between Conflict and Cholera in Nigeria and the Democratic Republic of the Congo." *Emerging Infectious Diseases* 28 (12): 2472–81. https://doi.org/10.3201/eid2812.212398.

Choi, Bernard C. K. 2012. "The Past, Present, and Future of Public Health Surveillance." *Scientifica* 2012: 1–26.

Clarke, Lorcan, Edith Patouillard, Andrew J. Mirelman, Zheng Jie Marc Ho, Tessa Tan-Torres Edejer, and Nirmal Kandel. 2022. "The Costs of Improving Health Emergency Preparedness: A Systematic Review and Analysis of Multi-Country Studies." *eClinicalMedicine* 44 (February): 101269. https://doi.org/10.1016/j.eclinm.2021.101269.

Cutler, David M., and Lawrence H. Summers. 2020. "The COVID-19 Pandemic and the $16 Trillion Virus." *JAMA* 324 (15): 1495. https://doi.org/10.1001/jama.2020.19759.

De Vries, Linda, Marion Koopmans, Alec Morton, and Pieter Van Baal. 2021. "The Economics of Improving Global Infectious Disease Surveillance." *BMJ Global Health* 6 (9): e006597. https://doi.org/10.1136/bmjgh-2021-006597.

Donelle, Lorie, Leigha Comer, Brad Hiebert, Jodi Hall, Jacob J. Shelley, Maxwell J. Smith, Anita Kothari, et al. 2023. "Use of Digital Technologies for Public Health Surveillance during the COVID-19 Pandemic: A Scoping Review." *DIGITAL HEALTH* 9 (January): 205520762311732. https://doi.org/10.1177/20552076231173220.

Dureab, Fekri, Maysoon Al-Sakkaf, Osan Ismail, Naasegnibe Kuunibe, Johannes Krisam, Olaf Müller, and Albrecht Jahn. 2019. "Diphtheria Outbreak in Yemen: The Impact of Conflict on a Fragile Health System." *Conflict and Health* 13 (1): 19. https://doi.org/10.1186/s13031-019-0204-2.

Elmahal, Osman M., Ali Abdullah, Manal K. Elzalabany, Huda Haidar Anan, Dalia Samhouri, and Richard John Brennan. 2022. "Public Health Emergency Operation Centres: Status, Gaps and Areas for Improvement in the Eastern Mediterranean Region." *BMJ Global Health* 7 (Suppl 4): e008573. https://doi.org/10.1136/bmjgh-2022-008573.

Fan, Victoria Y., Eleni Smitham, Lydia Regan, Pratibha Gautam, Ole Norheim, Javier Guzman, and Amanda Glassman. 2023. "Strategic Investment in Surveillance for Pandemic Preparedness: Rapid Review and Roundtable Discussion." CGD Policy Paper 298, Center for Global Development, Washington, DC. https://doi.org/10.13140/RG.2.2.24442.67520.

FAO (Food and Agriculture Organization of the United Nations), UNEP (United Nations Environment Programme), WHO (World Health Organization), and WOAH

(World Organisation for Animal Health). 2022. *One Health Joint Plan of Action (2022–2026): Working Together for the Health of Humans, Animals, Plants and the Environment*. Rome: FAO, UNEP, WHO, and WOAH. https://doi.org/10.4060/cc2289en.

Federspiel, Frederik, and Mohammad Ali. 2018. "The Cholera Outbreak in Yemen: Lessons Learned and Way Forward." *BMC Public Health* 18 (1): 1338. https://doi.org/10.1186/s12889-018-6227-6.

Frieden, Thomas R., Christopher T. Lee, Aaron F. Bochner, Marine Buissonnière, and Amanda McClelland. 2021. "7-1-7: An Organising Principle, Target, and Accountability Metric to Make the World Safer from Pandemics." *The Lancet* 398 (10300): 638–40. https://doi.org/10.1016/S0140-6736(21)01250-2.

Giattino, Charlie, Hannah Ritchie, Esteban Ortiz-Ospina, Lucas Rodés-Guirao, Joe Hasell, and Max Roser. 2020. "Excess Mortality during the Coronavirus Pandemic (COVID-19)." *Our World in Data*, March 5, 2020. https://ourworldindata.org/excess-mortality-covid.

Gibb, Rory, David W. Redding, Kai Qing Chin, Christl A. Donnelly, Tim M. Blackburn, Tim Newbold, and Kate E. Jones. 2020. "Zoonotic Host Diversity Increases in Human-Dominated Ecosystems." *Nature* 584 (7821): 398–402. https://doi.org/10.1038/s41586-020-2562-8.

Gossner, Céline M., Laurence Marrama, Marianne Carson, Franz Allerberger, Paolo Calistri, Dimitrios Dilaveris, Sylvie Lecollinet, et al. 2017. "West Nile Virus Surveillance in Europe: Moving towards an Integrated Animal-Human-Vector Approach." *Eurosurveillance* 22 (18). https://doi.org/10.2807/1560-7917.ES.2017.22.18.30526.

Hampton, Lee M., Hope L. Johnson, and Seth F. Berkley. 2022. "Diagnostics to Make Immunisation Programmes More Efficient, Equitable, and Effective." *The Lancet Microbe* 3 (4): e242–43. https://doi.org/10.1016/S2666-5247(22)00038-6.

Hampton, Lee M., Francisco Luquero, Alejandro Costa, Anais Legand, and Pierre Formenty. 2023. "Ebola Outbreak Detection and Response since 2013." *The Lancet Microbe* 4 (9): e661–62. https://doi.org/10.1016/S2666-5247(23)00136-2.

Hassan, Assad, G. U. Mustapha, Bola B. Lawal, Aliyu M. Na'uzo, Raji Ismail, Eteng Womi-Eteng Oboma, Oyeronke Oyebanji, et al. 2018. "Time Delays in the Response to the Neisseria Meningitidis Serogroup C Outbreak in Nigeria – 2017." *PLOS One* 13 (6): e0199257. https://doi.org/10.1371/journal.pone.0199257.

Hayman, David T. S., Wiku B. Adisasmito, Salama Almuhairi, Casey Barton Behravesh, Pépé Bilivogui, Salome A. Bukachi, Natalia Casas, et al. 2023. "Developing One Health Surveillance Systems." *One Health* 17 (December): 100617. https://doi.org/10.1016/j.onehlt.2023.100617.

Herida, Magid, Benoit Dervaux, and Jean-Claude Desenclos. 2016. "Economic Evaluations of Public Health Surveillance Systems: A Systematic Review." *European Journal of Public Health* 26 (4): 674–80. https://doi.org/10.1093/eurpub/ckv250.

IPPPR (Independent Panel for Pandemic Preparedness and Response). 2023. "COVID-19: Make It the Last Pandemic." IPPPR. https://theindependentpanel.org/wp-content/uploads/2021/05/COVID-19-Make-it-the-Last-Pandemic_final.pdf.

ITU (International Telecommunication Union). 2022. *Global Connectivity Report 2022*. Geneva: ITU.

Jain, Vageesh, Ashley Sharp, Matthew Neilson, Daniel G. Bausch, and Thomas Beaney. 2022. "Joint External Evaluation Scores and Communicable Disease Deaths: An Ecological Study on the Difference between Epidemics and Pandemics." *PLOS Global Public Health* 2 (8): e0000246. https://doi.org/10.1371/journal.pgph.0000246.

Jombart, Thibaut, Christopher I. Jarvis, Samuel Mesfin, Nabil Tabal, Mathias Mossoko, Luigino Minikulu Mpia, Aaron Aruna Abedi, et al. 2020. "The Cost of Insecurity: From Flare-Up to Control of a Major Ebola Virus Disease Hotspot during the Outbreak in the Democratic Republic of the Congo, 2019." *Eurosurveillance* 25 (2). https://doi.org/10.2807/1560-7917.ES.2020.25.2.1900735.

Jones, Kate E., Nikkita G. Patel, Marc A. Levy, Adam Storeygard, Deborah Balk, John L. Gittleman, and Peter Daszak. 2008. "Global Trends in Emerging Infectious Diseases." *Nature* 451 (7181): 990–93. https://doi.org/10.1038/nature06536.

Juneau, Carl-Etienne, Tomas Pueyo, Matt Bell, Genevieve Gee, Pablo Collazzo, and Louise Potvin. 2022. "Lessons from Past Pandemics: A Systematic Review of Evidence-Based, Cost-Effective Interventions to Suppress COVID-19." *Systematic Reviews* 11 (1): 90. https://doi.org/10.1186/s13643-022-01958-9.

Jutla, Antarpreet, Elizabeth Whitcombe, Nur Hasan, Bradd Haley, Ali Akanda, Anwar Huq, Munir Alam, et al. 2013. "Environmental Factors Influencing Epidemic Cholera." *American Journal of Tropical Medicine and Hygiene* 89 (3): 597–607. https://doi.org/10.4269/ajtmh.12-0721.

Kahn, Rebecca, Ayesha S. Mahmud, Andrew Schroeder, Luis Hernando Aguilar Ramirez, John Crowley, Jennifer Chan, and Caroline O. Buckee. 2019. "Rapid Forecasting of Cholera Risk in Mozambique: Translational Challenges and Opportunities." *Prehospital and Disaster Medicine* 34 (05): 557–62. https://doi.org/10.1017/S1049023X19004783.

Kilaru, Pruthvi, Dustin Hill, Kathryn Anderson, Mary B. Collins, Hyatt Green, Brittany L. Kmush, and David A. Larsen. 2023. "Wastewater Surveillance for Infectious Disease: A Systematic Review." *American Journal of Epidemiology* 192 (2): 305–22. https://doi.org/10.1093/aje/kwac175.

Kongelf, A., T. Tingberg, A. L. McClelland, M. C. Jean, and B. D. Dalziel. 2016. "Community-Based Cholera Surveillance by Volunteers with Mobile Phones: A Case Study from Western Area, Haiti." *International Journal of Infectious Diseases* 53 (December):115–16. https://doi.org/10.1016/j.ijid.2016.11.289.

Kouadio, Isidore K., Taro Kamigaki, and Hitoshi Oshitani. 2010. "Measles Outbreaks in Displaced Populations: A Review of Transmission, Morbidity and Mortality Associated Factors." *BMC International Health and Human Rights* 10 (1): 5. https://doi.org/10.1186/1472-698X-10-5.

Kraay, Alicia N. M., Kristin N. Nelson, Conan Y. Zhao, David Demory, Joshua S. Weitz, and Benjamin A. Lopman. 2021. "Modeling Serological Testing to Inform Relaxation of Social Distancing for COVID-19 Control." *Nature Communications* 12 (1): 7063. https://doi.org/10.1038/s41467-021-26774-y.

Kucharski, Adam J., Kiyojiken Chung, Maite Aubry, Iotefa Teiti, Anita Teissier, Vaea Richard, Timothy W. Russell, et al. 2023. "Real-Time Surveillance of International SARS-CoV-2 Prevalence Using Systematic Traveller Arrival Screening: An Observational Study." *PLOS Medicine* 20 (9): e1004283. https://doi.org/10.1371/journal.pmed.1004283.

Lam, Eugene, Amanda McCarthy, and Muireann Brennan. 2015. "Vaccine-Preventable Diseases in Humanitarian Emergencies among Refugee and Internally-Displaced Populations." *Human Vaccines & Immunotherapeutics* 11 (11): 2627–36. https://doi.org/10.1080/21645515.2015.1096457.

Ledesma, Jorge Ricardo, Christopher R. Isaac, Scott F. Dowell, David L. Blazes, Gabrielle V. Essix, Katherine Budeski, Jessica Bell, and Jennifer B. Nuzzo. 2023. "Evaluation of the Global Health Security Index as a Predictor of COVID-19 Excess Mortality Standardised for Under-Reporting and Age Structure." *BMJ Global Health* 8 (7): e012203. https://doi.org/10.1136/bmjgh-2023-012203.

Lee, Christopher, Sally Slavinski, Corinne Schiff, Mario Merlino, Demetre Daskalakis, Dakai Liu, Jennifer L. Rakeman, et al. 2017. "Outbreak of Influenza A(H7N2) among Cats in an Animal Shelter with Cat-to-Human Transmission—New York City, 2016." *Clinical Infectious Diseases* 65 (11): 1927–29. https://doi.org/10.1093/cid/cix668.

Lee, Elizabeth C., Andrew S. Azman, Joshua Kaminsky, Sean M. Moore, Heather S. McKay, and Justin Lessler. 2019. "The Projected Impact of Geographic Targeting of Oral Cholera Vaccination in Sub-Saharan Africa: A Modeling Study." *PLOS Medicine* 16 (12): e1003003. https://doi.org/10.1371/journal.pmed.1003003.

Lipsitch, Marc, and Mauricio Santillana. 2019. "Enhancing Situational Awareness to Prevent Infectious Disease Outbreaks from Becoming Catastrophic." In *Global Catastrophic*

Biological Risks, edited by Thomas V. Inglesby and Amesh A. Adalja, 59–74. Current Topics in Microbiology and Immunology. Cham: Springer International Publishing. https://doi.org/10.1007/82_2019_172.

Lotto Batista, Martín, Eleanor M. Rees, Andrea Gómez, Soledad López, Stefanie Castell, Adam J. Kucharski, Stéphane Ghozzi, et al. 2023. "Towards a Leptospirosis Early Warning System in Northeastern Argentina." *Journal of The Royal Society Interface* 20 (202): 20230069. https://doi.org/10.1098/rsif.2023.0069.

Marais, Gert, Diana Hardie, and Adrian Brink. 2023. "A Case for Investment in Clinical Metagenomics in Low-Income and Middle-Income Countries." *The Lancet Microbe* 4 (3): e192–99. https://doi.org/10.1016/S2666-5247(22)00328-7.

Masters, Nina B., Marisa C. Eisenberg, Paul L. Delamater, Matthew Kay, Matthew L. Boulton, and Jon Zelner. 2020. "Fine-Scale Spatial Clustering of Measles Nonvaccination That Increases Outbreak Potential Is Obscured by Aggregated Reporting Data." *Proceedings of the National Academy of Sciences* 117 (45): 28506–14. https://doi.org/10.1073/pnas.2011529117.

Mayigane, Landry Ndriko, Liviu Vedrasco, and Stella Chungong. 2023. "7-1-7: The Promise of Tangible Results through Agility and Accountability." *The Lancet Global Health* 11 (6): e805–6. https://doi.org/10.1016/S2214-109X(23)00167-5.

McKee, Clifton D., Ausraful Islam, Stephen P. Luby, Henrik Salje, Peter J. Hudson, Raina K. Plowright, and Emily S. Gurley. 2021. "The Ecology of Nipah Virus in Bangladesh: A Nexus of Land-Use Change and Opportunistic Feeding Behavior in Bats." *Viruses* 13 (2): 169. https://doi.org/10.3390/v13020169.

Mremi, Irene R., Janeth George, Susan F. Rumisha, Calvin Sindato, Sharadhuli I. Kimera, and Leonard E. G. Mboera. 2021. "Twenty Years of Integrated Disease Surveillance and Response in Sub-Saharan Africa: Challenges and Opportunities for Effective Management of Infectious Disease Epidemics." *One Health Outlook* 3 (1): 22. https://doi.org/10.1186/s42522-021-00052-9.

NTI (Nuclear Threat Initiative) and Johns Hopkins Center for Health Security, Bloomberg School of Public Health. 2021. "Global Health Security Index: Advancing Collective Action and Accountability amid Crisis." NTI, Washington, DC. https://ghsindex.org/wp-content/uploads/2021/12/2021_GHSindexFullReport_Final.pdf.

Nuzzo, Jennifer B., and Jorge R. Ledesma. 2023. "Why Did the Best Prepared Country in the World Fare So Poorly during COVID?" *Journal of Economic Perspectives* 37 (4): 3–22. https://doi.org/10.1257/jep.37.4.3.

OECD (Organisation for Economic Co-operation and Development). 2020. "Flattening the COVID-19 Peak: Containment and Mitigation Policies." OECD Policy Paper, OECD, Paris. https://www.oecd.org/en/publications/flattening-the-covid-19-peak-containment-and-mitigation-policies_e96a4226-en/full-report.html.

Oliver, Nuria, Bruno Lepri, Harald Sterly, Renaud Lambiotte, Sébastien Deletaille, Marco De Nadai, Emmanuel Letouzé, et al. 2020. "Mobile Phone Data for Informing Public Health Actions across the COVID-19 Pandemic Life Cycle." *Science Advances* 6 (23): eabc0764. https://doi.org/10.1126/sciadv.abc0764.

Oyebanji, Oyeronke, Fatima Ibrahim Abba, Oluwatosin Wuraola Akande, Everistus Chijioke Aniaku, Anwar Abubakar, John Oladejo, Olaolu Aderinola, et al. 2021. "Building Local Capacity for Emergency Coordination: Establishment of Subnational Public Health Emergency Operations Centres in Nigeria." *BMJ Global Health* 6 (10): e007203. https://doi.org/10.1136/bmjgh-2021-007203.

Poljanšek, K., M. Marin-Ferrer, L. Vernaccini, and L. Messina. 2018. *Incorporating Epidemics Risk in the INFORM Global Risk Index.* EUR 29603 EU. Luxembourg: Publications Office of the European Union. https://data.europa.eu/doi/10.2760/990429.

Rader, Benjamin, Samuel V. Scarpino, Anjalika Nande, Alison L. Hill, Ben Adlam, Robert C. Reiner, David M. Pigott, et al. 2020. "Crowding and the Shape of COVID-19 Epidemics." *Nature Medicine* 26 (12): 1829–34. https://doi.org/10.1038/s41591-020-1104-0.

Ratnayake, Ruwan, Meghan Tammaro, Amanda Tiffany, Anine Kongelf, Jonathan A Polonsky, and Amanda McClelland. 2020. "People-Centred Surveillance: A Narrative Review of

Community-Based Surveillance among Crisis-Affected Populations." *The Lancet Planetary Health* 4 (10): e483–95. https://doi.org/10.1016/S2542-5196(20)30221-7.

Redding, David W., Peter M. Atkinson, Andrew A. Cunningham, Gianni Lo Iacono, Lina M. Moses, James L. N. Wood, and Kate E. Jones. 2019. "Impacts of Environmental and Socio-economic Factors on Emergence and Epidemic Potential of Ebola in Africa." *Nature Communications* 10 (1): 4531. https://doi.org/10.1038/s41467-019-12499-6.

Redding, David W., Rory Gibb, Chioma C. Dan-Nwafor, Elsie A. Ilori, Rimamdeyati Usman Yashe, Saliu H. Oladele, Michael O. Amedu, et al. 2021. "Geographical Drivers and Climate-Linked Dynamics of Lassa Fever in Nigeria." *Nature Communications* 12 (1): 5759. https://doi.org/10.1038/s41467-021-25910-y.

Redding, David W., Sonia Tiedt, Gianni Lo Iacono, Bernard Bett, and Kate E. Jones. 2017. "Spatial, Seasonal and Climatic Predictive Models of Rift Valley Fever Disease across Africa." *Philosophical Transactions of the Royal Society B: Biological Sciences* 372 (1725). https://doi.org/10.1098/rstb.2016.0165.

Romanello, Marina, Claudia Di Napoli, Carole Green, Harry Kennard, Pete Lampard, Daniel Scamman, Maria Walawender, et al. 2023. "The 2023 Report of the *Lancet* Countdown on Health and Climate Change: The Imperative for a Health-Centred Response in a World Facing Irreversible Harms." *The Lancet* 402 (10419): 2346–94. https://doi.org/10.1016/S0140-6736(23)01859-7.

Ruiz, Santi. 2023. "How to Save Twenty Million Lives, with Dr. Mark Dybul." *Statecraft*, August 29, 2023. https://www.statecraft.pub/p/saving-twenty-million-lives.

Sharma, Siddhanth, Jaspreet Pannu, Sam Chorlton, Jacob L. Swett, and David J. Ecker. 2023. "Threat Net: A Metagenomic Surveillance Network for Biothreat Detection and Early Warning." *Health Security* 21 (5). https://doi.org/10.1089/hs.2022.0160.

Somda, Zana C., Helen N. Perry, Nancy R. Messonnier, Mamadou H. Djingarey, Salimata Ouedraogo Ki, and Martin I. Meltzer. 2010. "Modeling the Cost-Effectiveness of the Integrated Disease Surveillance and Response (IDSR) System: Meningitis in Burkina Faso." *PLOS One* 5 (9): e13044. https://doi.org/10.1371/journal.pone.0013044.

Tan, Chorh-Chuan. 2006. "SARS in Singapore—Key Lessons from an Epidemic." *Annals of the Academy of Medicine, Singapore* 35 (5): 345–49.

Tatem, A. J., D. J. Rogers, and S. I. Hay. 2006. "Global Transport Networks and Infectious Disease Spread." *Advances in Parasitology* 62: 293–343. https://doi.org/10.1016/S0065-308X(05)62009-X.

Thomson, Madeleine C., and Lawrence R. Stanberry. 2022. "Climate Change and Vectorborne Diseases." *New England Journal of Medicine* 387 (21): 1969–78. https://doi.org/10.1056/NEJMra2200092.

UN (United Nations). 2016. *Report of the Open-Ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction. Note by the Secretary-General.* New York: UN.

UNHCR (United Nations High Commissioner for Refugees). 2023. "Global Trends: Forced Displacement in 2022." UNHCR, Geneva. https://www.unhcr.org/global-trends-report-2022.

Vardavas, Constantine, Konstantinos Zisis, Katerina Nikitara, Ioanna Lagou, Valia Marou, Katerina Aslanoglou, Konstantinos Athanasakis, et al. 2023. "Cost of the COVID-19 Pandemic versus the Cost-Effectiveness of Mitigation Strategies in EU/UK/OECD: A Systematic Review." *BMJ Open* 13 (10): e077602. https://doi.org/10.1136/bmjopen-2023-077602.

WHO (World Health Organization). 2005. *Evaluating the Costs and Benefits of National Surveillance and Response Systems: Methodologies and Options*. Geneva: WHO.

WHO (World Health Organization). 2014. *Early Detection, Assessment and Response to Acute Public Health Events: Implementation of Early Warning and Response with a Focus on Event-Based Surveillance: Interim Version.* Geneva: WHO.

WHO (World Health Organization). 2015. *Framework for a Public Health Emergency Operations Centre: November 2015*. Geneva: WHO.

WHO (World Health Organization). 2016. *International Health Regulations (2005)* (third edition). Geneva: WHO.
WHO (World Health Organization). 2020. *Glossary of Health Emergency and Disaster Risk Management Terminology*. Geneva: WHO.
WHO (World Health Organization). 2021a. *Strategic Toolkit for Assessing Risks: A Comprehensive Toolkit for All-Hazards Health Emergency Risk Assessment*. Geneva: WHO.
WHO (World Health Organization). 2021b. *WHA74/9 - WHO's Work in Health Emergencies: Strengthening Preparedness for Health Emergencies*. Geneva: WHO. https://cdn.who.int/media/docs/default-source/documents/emergencies/a74_9add1-en.pdf.
WHO (World Health Organization). 2023a. *"Crafting the Mosaic": A Framework for Resilient Surveillance for Respiratory Viruses of Epidemic and Pandemic Potential.* Geneva: WHO. https://www.who.int/publications/i/item/9789240070288.
WHO (World Health Organization). 2023b. *Defining Collaborative Surveillance: A Core Concept for Strengthening the Global Architecture for Health Emergency Preparedness, Response, and Resilience (HEPR)*. Geneva: WHO. https://apps.who.int/iris/handle/10665/367927.
WHO (World Health Organization). 2023c. *Global Public Health Intelligence Report 2022*. Geneva: WHO.
WHO (World Health Organization). 2023d. *Guidance for Conducting a Country Early Action Review (EAR): Rapid Performance Improvement for Outbreak Detection and Response, 31 August 2023*. Geneva: WHO.
WHO (World Health Organization). 2023e. *Pandemic Influenza Preparedness Framework: Partnership Contribution High-Level Implementation Plan III 2024-2030*. Geneva: WHO.
WHO (World Health Organization). 2023f. *Strengthening the Global Architecture for Health Emergency Prevention, Preparedness, Response and Resilience*. Geneva: WHO.
WHO (World Health Organization). 2024. *Research Prioritization for Pandemic and Epidemic Intelligence: Technical Brief*. Geneva: WHO.
World Bank. 2022. "The Economic Impacts of the COVID-19 Crisis." Chapter 1 in *World Development Report 2022: Finance for an Equitable Recovery*. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1730-4.
Xu, Hanmeng, Kaiyue Zou, Juan Dent, Kirsten E. Wiens, Espoir Bwenge Malembaka, Godfrey Bwire, Placide Welo Okitayemba, et al. 2024. "Enhanced Cholera Surveillance to Improve Vaccination Campaign Efficiency." *Nature Medicine* 30: 1104–10. https://doi.org/10.1038/s41591-024-02852-8.
Yang, Jingyan, Shailja Vaghela, Benjamin Yarnoff, Solene De Boisvilliers, Manuela Di Fusco, Timothy Lee Wiemken, Moe H. Kyaw, et al. 2023. "Estimated Global Public Health and Economic Impact of COVID-19 Vaccines in the Pre-Omicron Era Using Real-World Empirical Data." *Expert Review of Vaccines* 22 (1): 54–65. https://doi.org/10.1080/14760584.2023.2157817.
Zeng, Wu, Hadia Samaha, Michel Yao, Steve Ahuka-Mundeke, Thomas Wilkinson, Thibaut Jombart, Dominique Baabo, et al. 2023. "The Cost of Public Health Interventions to Respond to the 10th Ebola Outbreak in the Democratic Republic of the Congo." *BMJ Global Health* 8 (10): e012660. https://doi.org/10.1136/bmjgh-2023-012660.