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Responding to Pandemic Risk: What Countries and Regions Can Do within the Constraints of Limited Global Cooperation and Solidarity

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ABSTRACT

The global response to pandemic threats remains inadequate, failing to translate the lessons of COVID-19 (coronavirus) into sustained investment and preparedness. The "panic and neglect" cycle persists, amplified by pandemic fatigue, denialism, misinformation, resistance to public health measures, and limited international cooperation. Against this backdrop, volume 2 of the fourth edition of *Disease Control Priorities* (*DCP4*) synthesizes scientific literature and expert knowledge to establish priorities for preventing, preparing for, and responding to future pandemics. This chapter synthesizes key insights from volume 2. It identifies priority actions based on the available evidence, while acknowledging that economic evaluations remain limited. Substantial reductions in pandemic risk can be achievable through targeted national and regional efforts, including the following:

- Recognizing the high ongoing pandemic risk (especially from influenza) and building adaptable, threat-agnostic frameworks rather than focusing solely on past experiences
- Implementing measures to minimize pathogen introduction from natural and human-made sources, and developing robust, layered early warning surveillance systems

- Rapidly characterizing novel pathogens to assess transmission and severity risks, and initiating timely containment actions based on available evidence, even if incomplete
- Investing in core public health functions (for example, surveillance and contact tracing), interlinked with resilient health care systems (for example, laboratory networks, oxygen supply, and emergency care) with adaptable surge capacity
- Tailoring public health and social measures to the specific pathogen, timing, and local socioeconomic context, moving beyond rigid preexisting pandemic plans
- Making critical investments in both rapid medical countermeasure development and regional manufacturing capacity, alongside streamlined regulatory pathways and robust delivery systems
- Establishing prearranged financing with swift disbursement based on clear, effectively designed triggers; prioritizing investments in dual-purpose infrastructure (for example, ventilation); and differentiating financial instruments for early (collective) versus late (domestic) needs.

DCP4 underscores that pandemic preparedness can be markedly improved through national and regional efforts. The annex to this chapter offers an initial prioritization framework synthesized from expert opinion. Although the evidence base for many interventions continues to evolve, this framework provides a structured starting point for context-specific adaptation and helps identify priority areas for future research and evaluation. Breaking the cycle of panic and neglect requires action now—not after the next pandemic begins.

INTRODUCTION

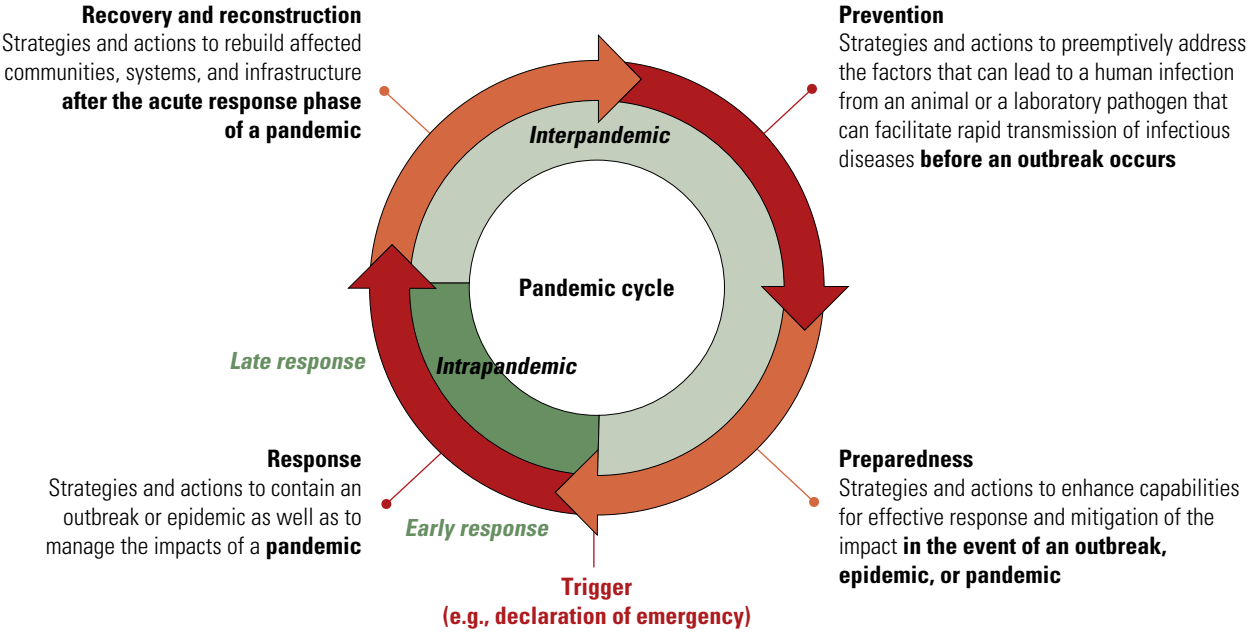
The fourth edition of *Disease Control Priorities* (*DCP4*) expands upon the foundation laid by previous DCP editions, translating health and economic evidence to help countries navigate a fair pathway to achieving universal health coverage. For the first time, an entire volume (volume 2) focuses on pandemics—a decision catalyzed by COVID-19 (coronavirus). Even before the pandemic, *DCP3* demonstrated foresight by dedicating two chapters to pandemic preparedness (Fan, Jamison, and Summers 2017; Madhav et al. 2017). The first chapter highlighted the magnitude of the economic risk posed by influenza pandemics, arguing that they received insufficient attention compared to other health priorities (Fan, Jamison, and Summers 2017). The second presented estimates of the probability of influenza pandemics, assessed the evidence on pandemic impacts (health, economic, social, and political), and synthesized the limited evidence on pandemic response measures and cost-effectiveness (Madhav et al. 2017). Like others (Hoffman and Silverberg 2018; International Working Group on Financing Preparedness 2017), this work

highlighted the persistent "panic and neglect" cycle driven by multiple barriers: systematic underestimation of pandemic risk, constrained budgets, disincentives for investing in global public goods, and challenges in preparing for hypothetical threats.

The work of curating *DCP4*, volume 2, has shown that these challenges have only intensified. Widespread fatigue and disillusionment with pandemic response measures and public health interventions after COVD-19 have further complicated preparedness efforts. Despite numerous high-level reports outlining necessary improvements for pandemic preparedness (Horton 2021; Sachs et al. 2022; The Independent Panel 2021), momentum for change remains weak. As Helen Clark and Ellen Johnson Sirleaf noted in June 2024, the enormous political challenges to negotiating and ratifying a pandemic treaty, along with international mistrust, have left critical vulnerabilities, allowing "pathogens to spill over, slip through, and spread fast" (Clark and Sirleaf 2024, 9).

This chapter synthesizes key insights from volume 2 of *DCP4*. The volume addresses the full pandemic cycle framework (figure 1.1): prevention (actions to reduce spillover risk and pathogen emergence before outbreaks occur), preparedness (building capabilities to respond effectively when threats emerge), response (containing outbreaks and mitigating pandemic impacts), and recovery (rebuilding systems and communities after a pandemic).

Figure 1.1 Framework for the Phases of the Pandemic Cycle



Source: Original figure created for this publication.

Given persistent global gridlock, the recommendations focus primarily on actions achievable at regional, national, and local levels. To support these recommendations, the annex to this chapter (comprising tables 1A.1–1A.6) presents a set of interventions prioritized through a synthesis of expert opinion. This chapter argues that targeted investments and reforms across all phases of the pandemic cycle can substantially reduce pandemic risks, even without global alignment and collective action. Despite a limited number of economic evaluations, the chapter identifies priority actions based on the available evidence and expert consensus. Although international reforms remain important, countries and regions need not wait for global consensus to strengthen their pandemic readiness.

REASSESSING PANDEMIC RISK: OVERCOMING RESISTANCE AND COMPLACENCY

During COVID-19, a common narrative emerged that such catastrophic events occur only once per century (Gates 2020). This narrative fosters complacency and undermines efforts to invest in preparedness (International Working Group on Financing Preparedness 2017). Today, the challenges facing pandemic preparedness extend beyond mere complacency. The experience of COVID-19 has transformed public attitudes in many societies from indifference into active resistance against public health measures, creating substantial barriers to implementing even basic preparedness initiatives (Nicolo et al. 2023).

However, new modeling by Madhav et al. in chapter 2 of this volume challenges the assumption that pandemics on the scale of COVID-19 are a once-in-a-century phenomenon. Using historical outbreak data and probabilistic modeling (while acknowledging the inherent uncertainties in any attempt to model extreme events), those authors estimate that the likelihood of another respiratory pandemic with mortality on the scale of COVID-19 or worse is roughly 20 percent over the next decade. On average, this translates to about 2.5 million estimated deaths annually, implying that their expected harm ranks on par with the greatest global infectious disease challenges we face.

The modeling finds that pandemic influenza presents the greatest threat, with expected annual losses roughly double those from epidemic novel coronaviruses, and greatly exceeding expected losses from filoviruses. This finding carries implications for pandemic preparedness. Although we must learn from COVID-19 response strategies and their varying success across nations, we cannot allow these lessons to narrow our focus to coronavirus-like threats alone. Influenza pandemics typically affect younger populations more severely than COVID-19 did—a key consideration for health care planning, public health and social measures (PHSM), and financial risk protection. Even within influenza pandemics, however, there is enormous variation: historical pandemics have varied widely in terms of their severity, duration, health impacts across age and demographic groups, and broader economic and societal impacts. Our preparedness frameworks must therefore

remain adaptable to diverse threat profiles, rather than becoming overly calibrated to historical experience (including our most recent experience).

OPPORTUNITIES FOR PREVENTION: ADDRESSING SPILLOVERS, BIOSAFETY, AND BIOSECURITY

Most pandemics have originated from zoonotic pathogens that crossed from animals to humans. The frequency and severity of these spillover events continue to increase, largely because of changes in land use, agriculture, and wildlife trade (Meadows et al. 2023). In principle, preventing such spillovers at or near their source could avert a pandemic (Morse et al. 2012). Dobson et al. (2020) estimate that interventions to achieve this goal might cost about US$20 billion–US$30 billion per year. Despite uncertainty about the effectiveness of these measures, which makes optimal investment levels difficult to pinpoint, the potential cost of inaction is significant.

Chapter 3 explains how preventing spillovers requires first detecting and monitoring potential pandemic pathogens in animal populations before they reach humans. Strengthening integrated surveillance systems across wildlife, livestock, human, and environmental health sectors (a "One Health" approach) is a prudent step toward prevention. Early detection in animal populations allows authorities to implement preventive measures before widespread human cases occur, making such surveillance systems critical for pandemic prevention.

Detection alone, however, is insufficient. Effective containment—the capacity to control animal disease outbreaks once identified—is also required. The ongoing spread of highly pathogenic avian influenza A (H5N1) demonstrates both the value of surveillance and the immense challenge of containment (Peacock et al. 2025). This virus originally emerged in wild birds, later spread to poultry, and now infects dairy cattle (Peacock et al. 2025). It has shown concerning adaptations that could enable human-to-human transmission (Garg et al. 2024). Despite detection of the virus, insufficient livestock biosecurity has allowed for extensive spread in dairy herds. This containment failure not only threatens animal health but also creates more opportunities for viral adaptation through repeated spillovers (Simoneau, Hirshfield, and Speer 2024). Achieving better control also faces systemic barriers: farmers risk significant economic losses from livestock culling or trade bans, and authorities may fear political or reputational damage from acknowledging outbreaks. Policy solutions, including fair compensation for losses, may help overcome these barriers by building trust and encouraging transparency (Rushton et al. 2005).

Further upstream, preventing wildlife-to-human spillovers requires different approaches than controlling livestock outbreaks. Reducing wildlife-to-human transmission risk calls for careful monitoring and regulation of markets and trade (Vora et al. 2023). The origins of COVID-19, likely linked to the sale of wildlife in Wuhan's live animal markets (Crits-Christoph et al. 2024), illustrate both the catastrophic potential of wildlife trade and the speed with which policy can change

once threats are taken seriously. China's 2020 wildlife trade ban demonstrates that rapid regulatory shifts are possible when political will aligns with public health imperatives (Koh, Li, and Lee 2021).

Chapter 4 illustrates how advancements in biotechnology present a separate source of pandemic risk beyond zoonotic spillovers. Although biological research is a cornerstone in reducing pandemic risks, as more facilities engage in high-level research, the potential for accidental pathogen release increases. Even minor laboratory mishaps can have major consequences, yet reporting of such incidents remains inconsistent. Unlike wildlife-human interfaces, the scale of which makes selective sampling necessary, laboratory biosafety requires universal surveillance. National and local authorities should, in line with the high-priority interventions outlined in table 1A.1, enforce mandatory lab biosafety standards, licensing, and incident reporting. Transparent reporting is essential for identifying common failure points, improving biosafety standards, and preventing unintentional outbreaks.

A parallel concern is the deliberate misuse of biotechnology, including the potential development of bioweapons. The accelerating capabilities of synthetic biology, automated laboratories, and artificial intelligence could enable smaller groups, or even individuals, to create or modify pathogens with pandemic potential (Pannu et al. 2024). This risk requires a dual approach to security. For legitimate research, governance frameworks must balance innovation with appropriate oversight of dual-use research (Wheeler 2025). However, malicious actors operating outside regulatory frameworks, like hostile states or criminal organizations, require different countermeasures. These countermeasures include robust intelligence capabilities, monitoring and regulation of equipment and material transfers (for example, DNA synthesis screening), and technical safeguards that limit a large language model's ability (like ChatGPT) to facilitate malicious acts. Addressing these interconnected threats requires coordination between scientific, security, and technology communities across borders (Lipsitch and Bloom 2012).

EARLY DETECTION AND IDENTIFYING NOVEL THREATS

Once a pathogen has emerged in human populations, swift and accurate detection determines whether an outbreak is contained or escalates globally. Early identification provides a critical window for intervention, enabling timely resource allocation and response. Although understanding a pathogen's characteristics (for example, transmissibility and severity) is discussed in the next section, it bears emphasizing that timely and comprehensive detection lays the groundwork for these deeper assessments and the evidence-based decisions and actions they inform.

Frontline clinicians and diagnostic laboratories are often the first to raise the alarm (Hussein 2014; Lingappa et al. 2004; Mahase 2020; MMWR 1996, 2009; Pellejero-Sagastizábal et al., forthcoming). In December 2019, a cluster of atypical pneumonia flagged by Wuhan doctors signaled the earliest stage of the COVID-19 pandemic (The Independent Panel 2021). Relying solely on clinical vigilance can

delay detection, however, because new pathogens are rarely top-of-mind for busy practitioners and often suspected only after excluding common causes, potentially weeks into hospital care (Chappell et al. 2021; Ecker 2020; Pellejero-Sagastizábal et al., forthcoming). To catch outbreaks earlier will require more systematic approaches. Chapters 5 and 11 illustrate how strengthening passive surveillance with genomic sequencing offers a promising strategy. For instance, targeted sequencing of a representative subset of influenza and COVID-19 polymerase chain reaction (PCR) detections can track pathogen evolution and diversity, whereas more novel approaches, such as respiratory viral metagenomics for severe acute respiratory infection (SARI) may enable the detection of entirely new pathogens.[1] By moving beyond predefined test panels, genomic methods reduce the risk of missing emergent threats and may avert weeks or months of undetected community transmission (Chappell et al. 2021).

Pathogen genomics, although powerful, presents challenges for low-resource settings because of its cost and complexity (Marais, Hardie, and Brink 2023; WHO 2021). Investing in sequencing infrastructure, specialized reagents, and trained staff may not seem locally cost-effective when the threat of a new pathogen appears low (Marais, Hardie, and Brink 2023; WHO 2021); however, this calculation changes dramatically when viewed from a global perspective. The localized expense of surveillance is orders of magnitude smaller than the societal and economic costs averted by stopping a pathogen at its source. For this reason, genomic surveillance and early warning systems should be treated as a global public good that merits external financing and coordinated support. Under such arrangements, countries with fewer resources can begin with simpler, tiered approaches: initially focusing on foundational laboratory and surveillance capacity and then establishing targeted sequencing of a small subset of influenza or COVID-19 samples, and referring more unusual or complex cases to regional reference laboratories for more advanced, untargeted sequencing. Over time, broader capacity to monitor febrile or respiratory illnesses can be expanded, enabling earlier detection and characterization of zoonotic threats that may spill over without yet transmitting from human to human.

Alongside clinical genomic sequencing, wastewater surveillance offers a complementary, relatively inexpensive approach (lower in cost per person than individual testing) for early detection (Sanjak et al. 2024). Municipal systems typically require substantial numbers of infected individuals to produce a detectable signal; however, targeted sampling in high-risk or high-traffic nodes (such as airports or hospitals) may yield earlier insights because such sampling requires fewer cases to produce a measurable signal (Morfino 2022). This approach can be particularly valuable in areas with limited clinical testing capacity or where health care access barriers exist.

RAPID CHARACTERIZATION AND CONTAINMENT

When a novel pathogen is detected, rapid characterization of its epidemiological and molecular features is essential. That initial assessment determines the public

health risk, guides immediate containment measures, and informs the development of countermeasures. A key early task, clarifying whether human-to-human transmission is occurring, is achieved through epidemiological investigation and genomic sequencing. If transmissibility is low, targeted measures like case isolation and controlling the zoonotic source may halt the spread. If an outbreak shows efficient person-to-person spread, however, governments face a narrow window to avert wider dissemination. The early response hinges on understanding key parameters including transmissibility, severity, and the extent of asymptomatic and presymptomatic spread.

Initially, determining these key parameters relies on intensive epidemiological work: detailed case finding, contact tracing, and analysis of early transmission chains. If a pathogen spreads rapidly, however, these traditional outbreak investigation methods can be quickly overwhelmed. The sheer volume of cases can make individual-level tracing unsustainable, leaving public health authorities with an incomplete picture of the outbreak's true scale and speed. In such scenarios, broader surveillance tools become valuable. Although expanding PCR testing capacity is critical, early-stage bottlenecks in laboratory infrastructure and supply chains are common. Developing and mass-producing point-of-care tests, particularly as a prepandemic goal supported by global research and development efforts (table 1A.5), may offer a more viable way to rapidly scale testing. Complementing individual diagnostics, wastewater surveillance can help track the extent of community spread. In several cities during the COVID-19 omicron wave, wastewater monitoring often predicted spikes 5–10 days before official case counts rose, providing valuable lead time for interventions (Cheng et al. 2023; Torabi et al. 2023).

Even with robust surveillance it may still be unclear whether the outbreak will evolve into a pandemic and cause significant harm. This uncertainty necessitates acting on incomplete information. Rapid risk assessment and decisive action, even with suggestive evidence, are more effective than waiting for certainty when the potential consequences are catastrophic. The COVID-19 timeline demonstrates this point: despite mounting evidence suggesting human-to-human transmission by mid-January 2020, many country, regional, and global health authorities waited for definitive proof before acting (The Independent Panel 2021). It took the World Health Organization (WHO) several weeks to gather sufficient evidence to confirm human transmission, and a full month to declare a public health emergency of international concern (The Independent Panel 2021). Major centers for disease control (for example, the European Centre for Disease Control and Prevention, and the US Centers for Disease Control and Prevention) showed similar hesitancy in their pathogen characterization and risk assessment, waiting for conclusive evidence before recommending important public health measures (ECDC 2020; Patel 2020).

Some Asia-Pacific economies moved faster. The Republic of Korea, Singapore, and Taiwan, China, quickly recognized presymptomatic and airborne

transmission risks, enabling early deployment of large-scale testing, border closures, contact tracing, and mask recommendations—measures other countries adopted months later (Jamison et al. 2024; Jamison and Wu 2021). Their experience illustrates a key pandemic response principle, often described as a "no regrets" approach: decisions must be made using available evidence weighing the relatively low costs of early intervention against the potentially catastrophic consequences of delay (Smallwood et al. 2021). These economies achieved lower transmission rates and less economic disruption throughout 2020 precisely because they acted on incomplete but suggestive information. Accordingly, this chapter lists PHSM decision frameworks as a key priority (table 1A.2) to prepare before the next pandemic (Jamison et al. 2024; Jamison and Wu 2021). Early interventions can often be adjusted or scaled back if the threat proves less severe than initially feared, whereas opportunities for effective containment, once missed, may be impossible to recover.

Political and social barriers, however, often block early action. Leaders hesitate to implement substantial measures that might later appear unnecessary if successful—creating a paradox in which effective prevention appears in hindsight to be an overreaction. Pathogens with moderate severity but high transmissibility, as witnessed with COVID-19, create a distinctive risk perception challenge. Unlike diseases with high case fatality rates that immediately trigger alarm (such as Ebola), pathogens that cause more moderate levels of severe disease or death appear manageable when viewing individual cases. Their high transmissibility, however, means that they can rapidly infect millions, transforming a seemingly moderate threat into one with catastrophic aggregate impact that can overwhelm health care capacity. This combination is particularly challenging for decision-making because the window for effective early intervention often closes before the cumulative harm becomes evident enough to overcome political resistance to disruptive containment measures. Data-driven triggers—which chapter 14 argues should be simple, transparent, objective, verifiable, and preagreed—may help overcome these obstacles by making decisions more technical than political.

Infectious disease modeling can help guide the early response through understanding core parameters such as reproduction number, incubation period, and asymptomatic transmission rates (Davies et al. 2020; Ferguson et al. 2020). By simulating different scenarios, models can also help project future cases, anticipate hospital surges, and evaluate which interventions might best reduce transmission. Whereas single models provide useful insights, ensemble approaches like the US COVID-19 Forecast Hub better account for uncertainties and varying assumptions (Howerton et al. 2023). Modeling effectiveness, however, depends on data quality and transparent communication of results and limitations, highlighting the need for integrated surveillance systems and a clear description of model assumptions, uncertainties, and scenario analyses.

When effective pathogen characterization, risk assessment, and timely response align—backed by political commitment—containment becomes possible. If containment is

deemed infeasible (Fraser et al. 2004), these same tools guide the shift to harm reduction and health care system resilience. Building these capabilities into preparedness plans enables faster mobilization during the critical containment window, or swift pivot to mitigation if that window closes (Craxì et al. 2020).

STRENGTHENING CORE PUBLIC HEALTH AND HEALTH SYSTEM CAPABILITIES

Chapters 5, 6, 7, and 12 emphasize that a core lesson from COVID-19 is the need for strong public health and health system capacities. Basic functions such as surveillance, contact tracing, laboratory networks, and clear protocols for isolation were pivotal in controlling transmission. Foundational investments such as building disease notification and contact tracing systems are essential for enabling seamless use of these functions. Japan and Korea demonstrated how applying these measures effectively, particularly before vaccines became available, can slow outbreaks (Imamura, Saito, and Oshitani 2021; Issac et al. 2020). Japan's approach was especially instructive. Health authorities focused on the "three Cs" (closed spaces, crowded places, and close-contact settings) and prioritized backward contact tracing in these high-risk environments. This targeted strategy helped authorities identify infection sources, disrupt transmission chains, and use limited public health resources more efficiently (Imamura, Saito, and Oshitani 2021; Imamura et al. 2020).

Investing in foundational health care capabilities, especially oxygen systems, basic clinical care, and essential diagnostics (refer to the high priority health system interventions in table 1A.2), may be one of the highest-priority actions nations can take, as chapters 11 and 12 illustrate. These core capabilities serve dual purposes: they strengthen routine care for chronic conditions while providing surge capacity for outbreaks. The tragic oxygen shortages during India's Delta wave in 2021 highlighted this critical need: hospitals simply could not maintain adequate oxygen supplies as demand surged (Acosta et al. 2022; Sachs et al. 2022). Effective oxygen delivery requires reliable electricity, enabling facilities to generate oxygen on-site rather than relying on transported cylinders, thus providing greater scalability and lower long-term costs.

All core capabilities must include surge capacity. COVID-19 showed how rapidly demands can escalate across all aspects of response, from contact tracing teams to laboratory networks to hospital beds (Imamura, Saito, and Oshitani 2021; Sachs et al. 2022). Many countries struggled to expand these systems during the crisis, creating bottlenecks that undermined effective response. Building flexibility into routine systems, with clear escalation protocols and regular scenario exercises, enables more rapid and effective scale-up when needed. This approach helps health systems manage both the initial surge of cases and the sustained pressure of a full pandemic.

PUBLIC HEALTH AND SOCIAL MEASURES: BALANCING EVIDENCE, TIMING, AND CONTEXT

COVID-19 prompted governments worldwide to implement a broad range of PHSM, from mask mandates to complete lockdowns. As chapters 6 and 8 explain, however, strong evidence on the effectiveness of each individual measure remains limited. Evaluating these interventions has been difficult because many countries (and jurisdictions within countries) introduced multiple measures simultaneously, with different degrees of strictness, in varying social and economic contexts (Talic et al. 2021). Still, comparing how different nations responded has offered useful insights on designing and implementing PHSM.

A key lesson is that PHSM deployment should be guided more by the specific epidemiological characteristics of the pathogen than by predefined pandemic plans (Huang et al. 2021). Decisions about stricter measures depend on factors such as how the pathogen spreads, its severity, and who is most at risk—all of which underscore the importance of gathering and analyzing evidence quickly in an emerging outbreak instead of simply applying strategies from past pandemics. Guided by preexisting influenza pandemic playbooks, many governments prioritized droplet- and fomite-based nonpharmaceutical interventions: physical distancing, hand hygiene, surface disinfection, and school closures (GIP 2019; Viner et al. 2020). Evidence from cluster investigations and an open letter by 239 scientists soon highlighted aerosol build-up in poorly ventilated venues as a dominant transmission route (Morawska and Milton 2020). Nevertheless, authoritative ventilation guidance and broad mask mandates often lagged by several months, especially in Europe and North America, compared with early adopters in East Asia.[2] Similarly, although pre-COVID-19 evidence suggested that travel restrictions would merely delay rather than prevent spread and would incur significant economic costs, during COVID-19 this delay proved important in buying time to prepare health systems and avoid overwhelming hospital capacity, especially before vaccines become available.

The timing of PHSM implementation strongly influences impact, particularly for highly restrictive measures such as stay-at-home orders (Zweig et al. 2021). Acting early when transmission is still low buys time to strengthen health systems, limit case numbers, and implement more targeted controls and shorter lockdowns; however, context matters significantly. India's nationwide lockdown in early 2020 demonstrated that strategies successful in wealthier countries can cause serious harm where social safety nets and financial support are weaker (Miguel and Mobarak 2022). This problem underscores the importance of tailoring public health responses to local conditions, with careful consideration of social and economic impacts, particularly in resource-limited settings.

JUMPSTARTING MEDICAL COUNTERMEASURE PRODUCTION AND DELIVERY

COVID-19 exposed profound inequities in access to medical countermeasures. High-income countries, representing just 19 percent of the world's adult population, secured over half of all COVID-19 vaccine doses through advance purchase agreements, as illustrated in chapter 9. By mid-2022, only 16 percent of people in low-income countries had received a single vaccine dose, compared to 80 percent in high-income countries. The pandemic also demonstrated unprecedented acceleration in vaccine development. Traditional vaccine development typically takes a decade or more, but mRNA platforms, overlapping phase I–III trials, and substantial investments compressed this timeline to under a year (GAO 2021). This achievement showed how concentrated global effort and innovative technologies could dramatically speed up the development of medical countermeasures.

The economic case for investing in accelerated vaccine development and manufacturing capacity is compelling. Chapter 9 compares "100-day vaccines" to a one-year development timeline under two pandemic scenarios. In a moderate scenario with an estimated 38 million deaths, fast vaccine creation prevented 99 percent of deaths and saved a combined US$53.7 trillion in mortality and economic losses. Under a more severe scenario with 146 million potential deaths, 97 percent of deaths were averted and US$191.6 trillion saved. Although equitable distribution enhanced these benefits, the greatest gains came from speed of development and deployment. Achieving the full scale of these benefits depends critically on having sufficient manufacturing capacity in place before a pandemic strikes. After the first COVID-19 vaccines were authorized, supply constraints were the main bottleneck to increasing global coverage through most of 2021.[3] Chapter 10 estimates that, to build this capacity, investing approximately US$60 billion up front and US$5 billion annually to build worldwide production capacity could yield US$500 billion in net present value over 10 years.

Geographically distributed manufacturing capacity improves resilience by insulating supply from export controls and purchasing power imbalances. During COVID-19, nations with strong purchasing power dominated vaccine supply, and manufacturing countries occasionally restricted exports (Duke Global Health Institute 2020). Although regional production may incur higher peacetime costs, it provides protection against supply nationalism. Smaller economies can share the fixed costs by establishing joint manufacturing hubs, which in interpandemic periods can produce routine adult influenza and COVID-19 vaccines. In many low-income settings, however, demand for seasonal influenza vaccines remains low, partly because its moderate efficacy and uncertain cost-effectiveness weaken the case for large public procurement (Gharpure et al. 2022).

Regulatory frameworks and delivery systems require equal attention to ensure that innovations translate into impact. Swift rollout of vaccines, diagnostics, and

treatments depends on streamlined regulatory approvals and robust clinical trial networks capable of rapidly evaluating new candidates (Mak et al. 2020; Wright et al. 2023). During COVID-19, WHO's Emergency-Use Listing and regional joint-review platforms such as the African Vaccine Regulatory Forum provided expedited pathways that dramatically shortened the usual regulatory timeline, allowing vaccines and other countermeasures to reach patients far sooner than would have been possible under routine procedures (Mak et al. 2020; Wright et al. 2023).

Meanwhile, last-mile delivery depends on resilient cold-chain logistics, well-trained health care workers, and proactive community engagement to foster trust and counter misinformation. Unlike typical mass vaccination campaigns for diseases like measles or polio that rely on substantial external support, pandemic vaccination efforts must often be scaled using local resources, because many countries simultaneously compete for scarce resources. COVID-19 highlighted how even abundant supplies can fail to achieve widespread coverage in a timely manner if public health systems do not receive sufficient resources or if misinformation erodes confidence. Strengthening these foundational elements (both upstream in regulatory processes and downstream in distribution) can accelerate equitable access and maximize the effectiveness of pandemic response efforts.

REFORMING PANDEMIC FINANCING ACROSS THE PANDEMIC CYCLE

Chapter 13 explains how COVID-19 exposed critical weaknesses in global health financing. Reliance on multiple organizations and disparate funding mechanisms increased complexity and slowed the mobilization of resources. Most financing was negotiated during the outbreak rather than prearranged, leading to avoidable delays when rapid action was essential. These delays in securing and distributing resources hindered early containment efforts and later attempts to reduce morbidity and mortality. Wealthier countries secured supplies more swiftly, exacerbating global inequities. New initiatives like COVID-19 Vaccines Global Access (commonly known as COVAX), launched to promote equitable vaccine access, arrived late and were overshadowed by individual countries' bilateral purchasing. Although international coordination remains important to address these disparities, current geopolitical realities, such as the United States' withdrawal from WHO and significant cuts to its international aid, underscore the need for alternative approaches. Strengthening regional financing mechanisms (such as the African Union's African Vaccine Acquisition Trust and the Association of Southeast Asian Nations' COVID-19 response fund) could provide a more reliable and agile solution, allowing funds to be activated quickly and managed more efficiently than through global efforts alone.

Regional financing could support pandemic prevention and preparedness activities that function as global public goods—activities that safeguard every country by lowering both the chance that new pathogens emerge and the speed at which they spread. To ensure that regional or national investments genuinely boost these capacities, however, chapter 13 recommends the use of clear and independently verified metrics for readiness. Such indicators may be drawn from frameworks like WHO's International Health Regulations (or a comparable system) and tied to incentive-based funding, ensuring that resources directly strengthen prevention. Priority should go to building dual-purpose infrastructure (such as laboratory networks, surveillance systems, and clinical care and public health workforces) that both improve routine health care delivery and bolster outbreak response capacity. Countries with greater capacity can bear a larger share of these costs, whereas lower-income nations will require collective regional financing to address critical gaps. Whether funded domestically or through pooled mechanisms, these efforts contribute to global health security by strengthening frontline defenses against emerging threats.

Chapters 13 and 14 also draw attention to the need for clear, predefined release mechanisms to enable swift early outbreak response. The system should operate like a circuit breaker, releasing funds when key thresholds are met without requiring lengthy approval processes. A combination of contingency funds and pandemic insurance could provide this rapid funding, with preset agreements governing how and when money flows. Early regional collaboration carries strong incentives for all parties: swift, coordinated action at the outset of an outbreak serves collective interests, similar to how (as chapter 13 illustrates) containing a small fire protects an entire neighborhood from widespread damage.

In contrast, late response and reconstruction efforts primarily address domestic concerns. Although humanitarian considerations might justify external assistance, the incentive for collective self-interest is not there. Continuing the fire analogy made in chapter 13, although neighbors might help extinguish the blaze, responsibility for repairs and rebuilding generally falls on the homeowner. For this phase, prepurchased pandemic insurance, prearranged contingent loans, or grants act as essential financial safeguards. These mechanisms, tailored to a country's ability to pay, can provide a practical path to recovery.

CONCLUSION

In summary, this second volume of *DCP4* confirms that the challenges highlighted in prior editions—neglected pandemic risks, weak preparedness, and political inertia—have only intensified. Nevertheless, this volume identifies clear opportunities for meaningful progress at national and regional levels. Among the top of these insights is that early decisive action based on incomplete information often achieved better outcomes than waiting

for certainty. The COVID-19 pandemic also highlighted significant gaps across the preparedness and response spectrum—from surveillance and health system readiness to equitable access to countermeasures and the importance of context-specific public health measures. The expert analysis and evidence synthesized in this volume demonstrates that timely, evidence-based, and context-specific measures can save millions of lives and trillions in economic losses, even in today's era of fractured global cooperation.

ANNEX 1A

Tables 1A.1–1A.6 present a set of interventions prioritized through a synthesis of expert opinion. The interventions specifically address pandemic prevention, preparedness, and response rather than broader global health priorities. This prioritization considered factors such as potential impact, feasibility, and cost, aiming to identify interventions offering significant value in pandemic prevention, preparedness, and response. The set of interventions is not exhaustive. Interventions are delineated for both national/local (tables 1A.1–1A.3) and global/regional (tables 1A.4–1A.6) contexts. Because of the currently limited evidence base for many interventions in diverse low- and middle-income country settings, the priorities should be considered tentative and are intended to stimulate context-specific analysis and guide future research to build a more robust evidence base. For global/regional contexts, tables focus on high-priority strategic interventions requiring international collaboration and coordination.

The national/local tables distinguish two key intervention categories: targeted measures refer to test, trace, isolate, and quarantine programs focused on identifying infectious individuals and their contacts; and PHSM encompass populationwide interventions such as gathering limits, mask mandates, ventilation improvements, and border controls. The tables use relative cost indicators ($, $$, $$$) for broad comparative prioritization of financial investment within a low- or middle-income country setting:

- $ **(low cost).** Modest financial resources (for example, policy, coordination, and leveraging existing resources)
- $$ **(medium cost).** Substantial investment (for example, comprehensive training, new protocols/equipment, and moderate infrastructure)
- $$$ **(high cost).** Significant financial outlay (for example, large-scale infrastructure, extensive technology, and broad multisectoral programs).

Table 1A.1 Pandemic Prevention Prioritization, National/Local

Priority	High	Medium	Low
One Health	• Implement livestock biosecurity. $$ • Establish intersectoral One Health coordination (risk assessment and data sharing). $ • Train frontline human/animal health staff within hot spots in zoonoses. $$	• Conduct animal-human interface surveillance (sentinel surveillance with sampling and sequencing at hot spots). $$ • Implement wet market risk reduction (licensing and regulation). $$ • Implement livestock vaccination. $$	• Reduce deforestation. $$$
Biosafety/biosecurity	• Enforce mandatory lab biosafety standards, licensing, and incident reporting. $ • Implement biological research governance (review boards and risk-benefit assessments). $$	• Invest in biorisk workforce (training, career paths, and certification). $$ • Tabletop exercises for accidental or deliberate threats. $$	

Source: Original table compiled for this report.

Note: $ = low cost; $$ = medium cost; $$$ = high cost.

Table 1A.2 Pandemic Preparedness Prioritization, National/Local

Priority	High	Medium	Low
Targeted measures	• Build local capacity for contact tracing. $$ • Plan repurposing of existing venues for isolation/quarantine facilities. $	• Plan to support home isolation and quarantine. $ • Develop digital tools to support contact tracing. $$	• Construct purpose-built isolation/quarantine facilities. $$$
PHSM	• Establish PHSM evidence-based decision frameworks. $ • Develop and maintain essential service continuity plans. $ • Develop community engagement and risk communication plans. $ • Implement low-cost ventilation/filtration upgrades. $	• Define context-specific border control protocols (closure, screening, testing, and quarantine). $ • Develop hybrid work/education infrastructure and policies. $$ • Expand ventilation/filtration upgrades. $	• Support evidence generation to determine PHSM effectiveness. $$$
Health systems	• Develop clinical care surge plans. $ • Invest in dual-purpose capacity (emergency care and infrastructure/workforce). $$ • Strengthen critical supply chains (for example, oxygen, PPE, and therapeutics). $$	• Ensure universal basic/advanced life support training and equipment. $$ • Develop modules to rapidly expand critical care competencies during emergencies. $$	• Strengthen advanced care capabilities (ECMO and renal replacement) at referral centers. $$$ • Develop adult immunization delivery platforms. $$$

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Table 1A.2 Pandemic Preparedness Prioritization, National/Local (continued)

Priority	High	Medium	Low
Surveillance	• Strengthen disease notification systems. $$ • Build essential public health lab capacity. $$ • Strengthen syndromic and event-based surveillance capabilities. $$	• Establish clinical-laboratory data link. $$ • Build genomic surveillance. $$ • Implement wastewater monitoring in targeted settings. $$ • Build epidemological modeling capabilities. $$	• Implement comprehensive genomic and wastewater surveillance. $$$
Products and manufacturing	• Develop rapid procurement processes. $ • Build and manage stockpiles. $$ • Invest in cold chain infrastructure. $ • Establish expedited regulatory review for emergencies. $ • Establish lines of credit to finance at-risk capacity investments. $$	• Develop local manufacturing capabilities for essential countermeasures. $$	• Invest in full-scale countermeasure development. $$$

Source: Original table compiled for this report.

Note: ECMO = extracorporeal membrane oxygenation; PHSM = public health and social measures; PPE = personal protective equipment; $ = low cost; $$ = medium cost; $$$ = high cost.

Table 1A.3 Pandemic Response Prioritization, National/Local

Priority	High	Medium	Low
Targeted measures	• Implement contact tracing for high-risk contexts/settings. $ • Provide guidance and support for self-isolation and quarantine. $ • Test symptomatic contacts. $$	• Expand contact tracing to low- to medium-risk contacts. $$ • Establish/repurpose isolation facilities. $$ • Deploy digital tools to support contact tracing. $	• Attempt comprehensive contact tracing for all potential exposures. $$$
PHSM	• Develop and activate emergency operations centers to coordinate surveillance, planning, and operational response. $ • Deliver timely, transparent, and factual risk communication. $ • Promote and enable core personal protective behaviors (for example, mask use and hand hygiene). $ • Improve ventilation and air quality in high-traffic areas, prioritizing low-cost solutions. $$ • Adopt school modifications that minimally disrupt education. $$	• Implement policies to reduce workplace density. $$ • Enforce capacity limits in public venues. $$$ • Implement mask mandates, particularly for specific high-risk indoor settings (for example, health care, aged care, and public transportation). $	• Implement broad restrictions on movement, nonessential business operations, or public access (lockdowns). $$$ • Implement widespread domestic travel restrictions. $$$ • Implement hotel quarantine and testing upon border entry. $$$

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Table 1A.3 Pandemic Response Prioritization, National/Local (continued)

Priority	High	Medium	Low
Health systems	• Activate national and subnational surge policies (as mentioned in table 1A.2). $$$ • Redirect resources to essential interventions: – Health centers and clinics (triage and basic life support, including oxygen) $$ – First-level hospitals (basic diagnostics and supportive care for respiratory failure and shock, such as mechanical ventilation). $$ • Manage supplies of key commodities, especially oxygen. $$$	• Maintain/protect essential nonpandemic services (including interventions in health benefits package). $$ • Expand rehabilitation services for patients following critical illness episodes and patients with postinfection disability syndromes. $$ • Expand supportive care for respiratory failure and shock to health centers. $$	• Designate select referral hospitals for – Advanced diagnostics and supportive care and $$$ – Advanced surgical and intensive care procedures. $$$
Surveillance	• Monitor and openly report key indicators (for example, cases, hospitalizations, and deaths). $ • Ensure laboratory capacity for essential pandemic diagnostics (for example, PCR and culture). $$ • Conduct targeted genomic surveillance. $$ • Apply epidemiological analyses to inform response actions. $	• Perform strategic wastewater monitoring. $$ • Deploy targeted asymptomatic testing in high-risk groups. $$ • Conduct epidemiological modeling to inform response planning. $$	• Undertake populationwide asymptomatic testing. $$$
Products and manufacturing	• Activate emergency procurement plans for diagnostics, therapeutics, oxygen, and basic PPE. $$$ • Streamline emergency regulatory pathways for pandemic products. $	• Boost domestic production of essential generic medicines, basic medical supplies (for example, PPE and sanitizers), and relevant raw materials. $$ • Participate actively in international clinical trials for new pandemic countermeasures. $	• Independently fund development of novel (early-stage) vaccine candidates. $$$ • Lead "moonshot" (high-risk, high-reward) biomedical R&D programs $$$

Source: Original table compiled for this report.

Note: PCR = polymerase chain reaction; PHSM = public health and social measures; PPE = personal protective equipment; R&D = research and development; $ = low cost; $$ = medium cost; $$$ = high cost.

Table 1A.4 Pandemic Prevention High-Priority Interventions, Global/Regional

Priority	High-priority interventions
One Health	• Develop coordinated animal-human interface surveillance networks (for example, testing humans at spillover hotspots and cross-border and intersectoral data sharing). • Implement harmonized wildlife trade regulation (coordinated monitoring, bans, and enforcement on the riskiest zoonotic species).
Biosafety/biosecurity	• Develop and implement international biosafety standards and peer-review audits. • Establish multilateral research governance norms and funding conditions (for example, mandatory risk reviews in donor requirements and journal policies). • Form a global DNA synthesis security consortium (access-controlled sequence databases, uniform screening protocols, and cross-border enforcement). • Establish a global registry of BSL3 and BSL4 labs, including both public and private.

Source: Original table compiled for this report.

Note: BSL3 = biosafety level 3; BSL4 = biosafety level 4.

Table 1A.5 Pandemic Preparedness High-Priority Interventions, Global/Regional

Priority	High-priority interventions
PHSM	• Support evidence generation to determine effectiveness of PHSM. • Invest in R&D for improved environmental controls (ventilation, filtration, and germicidal ultraviolet light) and PPE.
Surveillance	• Strengthen global pathogen data-sharing platform (genetic sequences, test protocols, and validation data). • Strengthen global pathogen alert and rapid-response systems (rules for escalating high-risk signals and triggering regional/global support). • Implement strategic genomic surveillance at novel pathogen emergence hot spots. • Implement and strengthen strategic wastewater surveillance at high-risk areas (for example, major transportation hubs). • Drive R&D for broad-spectrum point-of-care diagnostics.
Priority	**High-priority interventions**
Products and manufacturing	• Invest in "warm" (rapidly repurposable) global manufacturing capacity. • Fund R&D for countermeasure platform technologies (vaccines, therapeutics, and diagnostics). • Prioritize R&D for high-priority pathogens (for example, universal vaccines and broad-spectrum antivirals). • Strengthen global clinical trial infrastructure (for example, recruit preselected cohorts who have given consent ex ante). • Strengthen oxygen supply chain and production capacity. • Multilateral development banks should establish credit mechanisms to help low- and middle-income countries finance at-risk capacity investments in the event of a pandemic

Source: Original table compiled for this report.

Note: PHSM = public health and social measures; PPE = personal protective equipment; R&D = research and development.

Table 1A.6 Pandemic Response High-Priority Interventions, Global/Regional

Priority	High-priority interventions
PHSM	• Facilitate rapid evidence synthesis, and disseminate updated PHSM guidance for the current pathogen and its variants.
	• Support systematic evidence generation to evaluate PHSM guidance.
Surveillance	• Standardize and facilitate global reporting of core epidemiological indicators (for example, cases, deaths, hospitalizations).
	• Coordinate global surveillance (genomic, phenotypic), and enable rapid data sharing.
	• Provide global/regional epidemiological modeling, forecasting, and technical support to countries.
	• Conduct rapid risk assessments of transmission and disease potential to guide country responses.
	• Support and coordinate international wastewater surveillance to monitor pathogen trends.
Products and manufacturing	• Mobilize and coordinate global manufacturing capacity for the rapid scale-up of needed countermeasures.
	• Coordinate equitable global allocation and distribution of essential countermeasures (diagnostics, therapeutics, vaccines, and PPE).
	• Support and expedite the rapid development, evaluation (including clinical trials), and adaptation of countermeasures.
	• Coordinate global efforts to ensure access to medical oxygen and essential related clinical supplies.
	• Incentivize vaccine manufacturing firms to build at-risk capacity.
	• Use vaccine capacity efficiently (for example, "first doses first" policy).
	• Invest in a diverse portfolio of vaccine candidates (across vaccine platforms).

Source: Original table compiled for this report.

Note: PHSM = public health and social measures; PPE = personal protective equipment.

NOTES

1. World Health Organization, "Surveillance Case Definitions for ILI and SARI" (accessed February 22, 2025), https://www.who.int/teams/global-influenza-programme/surveillance-and-monitoring/case-definitions-for-ili-and-sari.
2. Our World in Data, "Face Covering Policies during the COVID-19 Pandemic" (accessed April 19, 2025), https://ourworldindata.org/grapher/face-covering-policies-covid.
3. World Health Organization, "CoVDP Frequently Asked Questions" (accessed May 12, 2025), https://www.who.int/news-room/questions-and-answers/item/covdp-frequently-asked-questions.

REFERENCES

Acosta, R. J., B. Patnaik, C. Buckee, M. V. Kiang, R. A. Irizarry, S. Balsari, and A. Mahmud 2022. "All-Cause Excess Mortality across 90 Municipalities in Gujarat, India, during the COVID-19 Pandemic (March 2020–April 2021)." *PLOS Global Public Health* 2 (8): e0000824.

Chappell, J. G., T. Tsoleridis, G. Clark, L. Berry, N. Holmes, C. Moore, M. Carlile, et al. 2021. "Retrospective Screening of Routine Respiratory Samples Revealed Undetected Community Transmission and Missed Intervention Opportunities for SARS-CoV-2 in the

United Kingdom." *Journal of General Virology* 102 (6). https://www.microbiologyresearch.org/content/journal/jgv/10.1099/jgv.0.001595.
Cheng, L., H. A. Dhiyebi, M. Varia, K. Atanas, N. Srikanthan, S. Hayat, H. Ikert, et al. 2023. "Omicron COVID-19 Case Estimates Based on Previous SARS-CoV-2 Wastewater Load, Regional Municipality of Peel, Ontario, Canada." *Emerging Infectious Diseases* 29 (8). https://wwwnc.cdc.gov/eid/article/29/8/22-1580_article.
Clark, H., and E. J. Sirleaf. 2024. "No Time to Gamble: Leaders Must Unite to Prevent Pandemics." The Independent Panel for Pandemic Preparedness & Response. https://theindependentpanel.org/wp-content/uploads/2024/06/The-Independent-Panel_No-time-to-gamble.pdf.
Craxì, L., M. Vergano, J. Savulescu, and D. Wilkinson. 2020. "Rationing in a Pandemic: Lessons from Italy." *Asian Bioethics Review* 12 (3): 325–30.
Crits-Christoph, A., J. I. Levy, J. E. Pekar, S. A. Goldstein, R. Singh, Z. Hensel, K. Gangavarapu, et al. 2024. "Genetic Tracing of Market Wildlife and Viruses at the Epicenter of the COVID-19 Pandemic." *Cell* 187 (19): 5468–82.
Davies, N. G., A. J. Kucharski, R. M. Eggo, A. Gimma, and W. J. Edmunds. 2020. "Effects of Non-pharmaceutical Interventions on COVID-19 Cases, Deaths, and Demand for Hospital Services in the UK: A Modelling Study." *The Lancet Public Health* 5 (7): e375–85.
Dobson, A. P., S. L. Pimm, L. Hannah, L. Kaufman, J. A. Ahumada, A. W. Ando, A. Bernstein, et al. 2020. "Ecology and Economics for Pandemic Prevention." *Science* 369 (6502): 379–81.
Duke Global Health Institute. 2020. "Will Low-Income Countries Be Left Behind When COVID-19 Vaccines Arrive?" *Research News*, November 9. https://globalhealth.duke.edu/news/will-low-income-countries-be-left-behind-when-covid-19-vaccines-arrive.
ECDC (European Centre for Disease Prevention and Control). 2020. "Rapid Risk Assessment: Cluster of Pneumonia Cases Caused by a Novel Coronavirus, Wuhan, China, 2020." ECDC. https://www.ecdc.europa.eu/en/publications-data/rapid-risk-assessment-cluster-pneumonia-cases-caused-novel-coronavirus-wuhan.
Ecker, D. J. 2020. "How to Snuff Out the Next Pandemic." *Scientific American*, May 18, 2020. https://www.scientificamerican.com/blog/observations/how-to-snuff-out-the-next-pandemic/.
Fan, V. Y., D. T. Jamison, and L. H. Summers. 2017. "The Loss from Pandemic Influenza Risk." In *Disease Control Priorities: Improving Health and Reducing Poverty* (third edition), Volume 9, edited by D. T. Jamison, H. Gelband, S. Horton, P. Jha, R. Laxminarayan, C. N. Mock, and R. Nugent. Washington, DC: World Bank. http://www.ncbi.nlm.nih.gov/books/NBK525291/.
Ferguson, N. M., D. Laydon, G. Nedjati-Gilani, N. Imai, K. Ainslie, M. Baguelin, S. Bhatia, et al. 2020. "Impact of Non-pharmaceutical Interventions (NPIs) to Reduce COVID-19 Mortality and Healthcare Demand." Report No. 9, Imperial College COVID-19 Response Team, Imperial College London. https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-NPI-modelling-16-03-2020.pdf.
Fraser, C., S. Riley, R. M. Anderson, and N. M. Ferguson. 2004. "Factors That Make an Infectious Disease Outbreak Controllable." *Proceedings of the National Academy of Sciences of the United States of America* 101 (16): 6146–51.
GAO (United States Government Accountability Office). 2021. "Operation Warp Speed: Accelerated COVID-19 Vaccine Development Status and Efforts to Address Manufacturing Challenges." GAO-21-319, GAO, Washington, DC. https://www.gao.gov/products/gao-21-319.
Garg, S., K. Reinhart, A. Couture, K. Kniss, C. T. Davis, M. K. Kirby, E. L. Murray, et al. 2024. "Highly Pathogenic Avian Influenza A(H5N1) Virus Infections in Humans." *New England Journal of Medicine* 392 (9): 843–54.

Gates B. 2020. "Responding to Covid-19—A Once-in-a-Century Pandemic?" *New England Journal of Medicine* 382 (18): 1677–79.

Gharpure, R., A. N. Chard, M. Cabrera Escobar, W. Zhou, M. M. Valleau, T. S. Yau, J. S. Bresee, et al. 2022. "Costs and Cost-Effectiveness of Influenza Illness and Vaccination in Low- and Middle-Income Countries: A Systematic Review from 2012 to 2022." *PLOS Medicine* 21 (1): e1004333.

GIP (Global Influenza Programme). 2019. "Non-pharmaceutical Public Health Measures for Mitigating the Risk and Impact of Epidemic and Pandemic Influenza." World Health Organization, Geneva. https://www.who.int/publications/i/item/non-pharmaceutical-public-health-measuresfor-mitigating-the-risk-and-impact-of-epidemic-and-pandemic-influenza.

Hoffman, S. J., and S. L. Silverberg. 2018. "Delays in Global Disease Outbreak Responses: Lessons from H1N1, Ebola, and Zika." *American Journal of Public Health* 108 (3): 329–33.

Horton, R. 2021. *The COVID-19 Catastrophe: What's Gone Wrong and How to Stop It Happening Again*. John Wiley & Sons.

Howerton, E., L. Contamin, L. C. Mullany, M. Qin, N. G. Reich, S. Bents, R. Borchering, et al. 2023. "Evaluation of the US COVID-19 Scenario Modeling Hub for Informing Pandemic Response under Uncertainty." *Nature Communications* 14 (1): 7260.

Huang, Q. S., T. Wood, L. Jelley, T. Jennings, S. Jefferies, K. Daniells, A. Nesdale, et al. 2021. "Impact of the COVID-19 Nonpharmaceutical Interventions on Influenza and Other Respiratory Viral Infections in New Zealand." *Nature Communications* 12: 1001.

Hussein, I. 2014. "The Story of the First MERS Patient." *Nature Middle East*, June 2, 2014. https://www.natureasia.com/en/nmiddleeast/article/10.1038/nmiddleeast.2014.134.

Imamura, T., T. Saito, and H. Oshitani. 2021. "Roles of Public Health Centers and Cluster-Based Approach for COVID-19 Response in Japan." *Health Security* 19 (2): 229–31.

Imamura, T., A. Watanabe, Y. Serizawa, M. Nakashita, M. Saito, M. Okada, A. Ogawa, et al. 2020. "Transmission of COVID-19 in Nightlife, Household, and Health Care Settings in Tokyo, Japan, in 2020." *JAMA Network Open* 6 (2): e230589.

International Working Group on Financing Preparedness. 2017. "From Panic and Neglect to Investing in Health Security." World Bank, Washington, DC. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/979591495652724770/from-panic-and-neglect-to-investing-in-health-security-financing-pandemic-preparedness-at-a-national-level.

Issac, A., S. Stephen, J. Jacob, V. Vr, R. V. Radhakrishnan, N. Krishnan, M. Dhandapani, et al. 2020. "The Pandemic League of COVID-19: Korea versus the United States, with Lessons for the Entire World." *Journal of Preventive Medicine and Public Health* 53 (4): 228–32.

Jamison, D. T., L. H. Summers, A. Y. Chang, O. Karlsson, W. Mao, O. F. Norheim, O. Ogbuoji, et al. 2024. "Global Health 2050: The Path to Halving Premature Death by Mid-century." *The Lancet* 404 (10462): 1561–614.

Jamison, D. T., and K. B. Wu. 2021. "The East–West Divide in Response to COVID-19." *Engineering* 7 (7): 936–47.

Koh, L. P., Y. Li, and J. S. H. Lee. 2021. "The Value of China's Ban on Wildlife Trade and Consumption." *Nature Sustainability* 4: 2–4. https://www.nature.com/articles/s41893-020-00677-0.

Lingappa, J. R., L. C. McDonald, P. Simone, and U. D. Parashar. 2004. "Wresting SARS from Uncertainty." *Emerging Infectious Diseases* 10 (2). https://wwwnc.cdc.gov/eid/article/10/2/03-1032_article.

Lipsitch, M., and B. R. Bloom. 2012. "Rethinking Biosafety in Research on Potential Pandemic Pathogens." *mBio* 3 (5).

Madhav, N., B. Oppenheim, M. Gallivan, P. Mulembakani, E. Rubin, and N. Wolfe. 2017. "Pandemics: Risks, Impacts, and Mitigation." In *Disease Control Priorities: Improving Health and Reducing Poverty* (third edition), Volume 9, edited by D. T. Jamison,

H. Gelband, S. Horton, P. Jha, R. Laxminarayan, C. N. Mock, and R. Nugent. Washington, DC: World Bank. http://www.ncbi.nlm.nih.gov/books/NBK525302/.
Mahase, E. 2020. "Coronavirus: Doctor Who Faced Backlash from Police after Warning of Outbreak Dies." *BMJ* 368: m528. https://www.bmj.com/content/368/bmj.m528.
Mak, T. K., J. C. Lim, P. Thanaphollert, G. N. Mahlangu, E. Cooke, and M. M. Lumpkin. 2020. "Global Regulatory Agility during COVID-19 and Other Health Emergencies." *BMJ* 369: m1575. https://www.bmj.com/content/369/bmj.m1575.long.
Marais, G., D. Hardie, and A. Brink. 2023. "A Case for Investment in Clinical Metagenomics in Low-Income and Middle-Income Countries." *The Lancet Microbe* 4 (3): e192–9.
Meadows, A. J., N. Stephenson, N. K. Madhav, and B. Oppenheim. 2023. "Historical Trends Demonstrate a Pattern of Increasingly Frequent and Severe Spillover Events of High -Consequence Zoonotic Viruses." *BMJ Global Health* 8 (11): e012026.
Miguel, E., and A. M. Mobarak. 2022. "The Economics of the COVID-19 Pandemic in Poor Countries." *Annual Review of Economics* 14: 253–85. https://www.annualreviews.org /content/journals/10.1146/annurev-economics-051520-025412.
MMWR (Morbidity and Mortality Weekly Report). 1996. "Pneumocystis Pneumonia—Los Angeles." *MMWR* 1996 (45): 729–33. https://www.cdc.gov/mmwr/preview/mmwrhtml /lmrk077.htm.
MMWR (Morbidity and Mortality Weekly Report). 2009. "Outbreak of Swine-Origin Influenza A (H1N1) Virus Infection—Mexico, March–April 2009." *MMWR* 2009 (58–Dispatch): 1–3. https://www.cdc.gov/mmwr/preview/mmwrhtml/mm58d0430a2.htm.
Morawska, L., and D. K. Milton. 2020. "It Is Time to Address Airborne Transmission of Coronavirus Disease 2019 (COVID-19)." *Clinical Infectious Diseases* 71 (9): 2311–13.
Morfino, R. C. 2022. "Notes from the Field: Aircraft Wastewater Surveillance for Early Detection of SARS-CoV-2 Variants—John F. Kennedy International Airport, New York City, August–September 2022." *Morbidity and Mortality Weekly Report* 72 (8): 210–11. https://www.cdc.gov/mmwr/volumes/72/wr/mm7208a3.htm.
Morse, S. S., J. A. K. Mazet, M. Woolhouse, C. R. Parrish, D. Carroll, W. B. Karesh, C. Zambrana-Torrelio, et al. 2012. "Prediction and Prevention of the Next Pandemic Zoonosis." *The Lancet* 380 (9857): 1956–65.
Nicolo, M., E. Kawaguchi, A. Ghanem-Uzqueda, D. Soto, S. Deva, K. Shanker, R. Lee, et al. 2023. "Characteristics Associated with Attitudes and Behaviors towards Mask Wearing during the COVID-19 Pandemic: The Trojan Pandemic Response Initiative." *BMC Public Health* 23 (1): 1968.
Pannu, J., S. Gebauer, G. McKelvey, A. Cicero, and T. Inglesby. 2024. "AI Could Pose Pandemic-Scale Biosecurity Risks. Here's How to Make It Safer." *Nature* 635 (8040): 808–11.
Patel A. 2020. "Initial Public Health Response and Interim Clinical Guidance for the 2019 Novel Coronavirus Outbreak—United States, December 31, 2019–February 4, 2020." *Morbidity and Mortality Weekly Report* 69 (5): 140–46. https://www.cdc.gov/mmwr /volumes/69/wr/mm6905e1.htm.
Peacock, T. P., L. Moncla, G. Dudas, D. VanInsberghe, K. Sukhova, J. O. Lloyd-Smith, M. Worobey, et al. 2025. "The Global H5N1 Influenza Panzootic in Mammals." *Nature* 637 (8045): 304–13.
Pellejero-Sagastizábal, G., C. Bulescu, N. Gupta, P. Jokelainen, E. Gkrania-Klotsas, A. Barac, A. Goorhuis, et al. Forthcoming. "Delayed Correct Diagnoses in Emerging Disease Outbreaks: Historical Patterns and Lessons for Contemporary Responses." *Clinical Microbiology and Infection*. https://www.clinicalmicrobiologyandinfection.com/article /S1198-743X%2825%2900169-7/fulltext.
Rushton, J., R. Viscarra, E. G. Bleich, and A. McLeod. 2005. "Impact of Avian Influenza Outbreaks in the Poultry Sectors of Five South East Asian Countries (Cambodia, Indonesia, Lao PDR, Thailand, Viet Nam) Outbreak Costs, Responses and Potential Long Term Control." *World's Poultry Science Journal* 61 (3): 491–514.

Sachs, J. D., S. S. A. Karim, L. Aknin, J. Allen, K. Brosbøl, F. Colombo, G. Barron, et al. 2022. "The *Lancet* Commission on Lessons for the Future from the COVID-19 Pandemic." *The Lancet* 400 (10359): 1224–80.

Sanjak, J. S., E. M. McAuley, J. Raybern, R. Pinkham, J. Tarnowski, N. Miko, B. Rasmussen, et al. 2024. "Wastewater Surveillance Pilot at US Military Installations: Cost Model Analysis." *JMIR Public Health and Surveillance* 10. https://www.sciencedirect.com/org/science/article/pii/S2369296024002576.

Simoneau, M., S. Hirshfield, and M. Speer. 2024. "The United States Needs to Step Up Its Response to Bird Flu." Center for Strategic and International Studies, December 19, 2024. https://features.csis.org/US-bird-flu-response.

Smallwood, C. A. H., I. Perehinets, J. S. Meyer, and D. Nitzen. 2021. "WHO's Emergency Response Framework: A Case Study for Health Emergency Governance Architecture." *Eurohealth* 27 (1): 20–25. https://iris.who.int/handle/10665/344935.

Talic, S., S. Shah, H. Wild, D. Gasevic, A. Maharaj, Z. Ademi, X. Li, et al. 2021. "Effectiveness of Public Health Measures in Reducing the Incidence of COVID-19, SARS-CoV-2 Transmission, and COVID-19 Mortality: Systematic Review and Meta-analysis." *BMJ* 375: e068302.

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

Torabi, F., G. Li, C. Mole, G. Nicholson, B. Rowlingson, C. R. Smith, R. Jersakova, et al. 2023. "Wastewater-Based Surveillance Models for COVID-19: A Focused Review on Spatio-temporal Models." *Heliyon* 9 (11): e21734.

Viner, R. M., S. J. Russell, H. Croker, J. Packer, J. Ward, C. Stansfield, O. Mytton, et al. 2020. "School Closure and Management Practices during Coronavirus Outbreaks including COVID-19: A Rapid Systematic Review." *The Lancet Child & Adolescent Health* 4 (5): 397–404.

Vora, N. M., L. Hannah, C. Walzer, M. M. Vale, S. Lieberman, A. Emerson, J. Jennings, et al. 2023. "Interventions to Reduce Risk for Pathogen Spillover and Early Disease Spread to Prevent Outbreaks, Epidemics, and Pandemics." *Emerging Infectious Diseases* 29 (3):e221079.

Wheeler, N. E. 2025. "Responsible AI in Biotechnology: Balancing Discovery, Innovation and Biosecurity Risks." *Frontiers in Bioengineering and Biotechnology* 13 (February). https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2025.1537471/full.

WHO (World Health Organization). 2021. *Genomic Sequencing of SARS-CoV-2: A Guide to Implementation for Maximum Impact on Public Health*. Geneva: WHO. https://www.who.int/publications-detail-redirect/9789240018440.

Wright, K., N. Aagaard, A. Y. Ali, C. Atuire, M. Campbell, K. Littler, A. Mandil, et al. 2023. "Preparing Ethical Review Systems for Emergencies: Next Steps." *BMC Medical Ethics* 24 (1): 92.

Zweig, S. A., A. J. Zapf, H. Xu, Q. Li, S. Agarwal, A. B. Labrique, D. H. Peters, et al. 2021. "Impact of Public Health and Social Measures on the COVID-19 Pandemic in the United States and Other Countries: Descriptive Analysis." *JMIR Public Health Surveillance* 7 (6): e27917.