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Innovations in Public Health Surveillance for Emerging Infections

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Abstract

Public health surveillance is defined as the ongoing, systematic collection, analysis, and interpretation of health data and is closely integrated with the timely dissemination of information that the public needs to know and upon which the public should act. Public health surveillance is central to modern public health practice by contributing data and information usually through a national notifiable disease reporting system (NNDRS). Although early identification and prediction of future disease trends may be technically feasible, more work is needed to improve accuracy so that policy makers can use these predictions to guide prevention and control efforts. In this article, we review the advantages and limitations of the current NNDRS in most countries, discuss some lessons learned about prevention and control from the first wave of COVID-19, and describe some technological innovations in public health surveillance, including geographic information systems (GIS), spatial modeling, artificial intelligence, information technology, data science, and the digital twin method. We conclude that the technology-driven innovative public health surveillance systems are expected to further improve the timeliness, completeness, and accuracy of case reporting during outbreaks and also enhance feedback and transparency, whereby all stakeholders should receive actionable information on control and be able to limit disease risk earlier than ever before.

INTRODUCTION

Public health surveillance is defined as the ongoing, systematic collection, analysis, and interpretation of health data that are essential to the planning, implementation, and evaluation of public health practice and is closely integrated with the timely dissemination of information that the public needs to know and upon which the public should act (75). Public health surveillance is central to modern public health practice by contributing data and information usually through a national notifiable disease reporting system (NNDRS), which, although named differently in various countries (e.g., **Table 1**), often refers to the case surveillance system for infectious and other reportable conditions (23). Among all functions of public health surveillance, early identification and accurate forecasting of the timing, intensity, and distribution of emerging infectious diseases have been of high priority. This is particularly true in the current context of the coronavirus disease 2019 (COVID-19) pandemic, which was caused by a novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). COVID-19 was declared as a public health emergency of international concern on January 30, 2020, and further as a pandemic by the World Health Organization (WHO) on March 11, 2020.

The numbers of identified COVID-19 infections and deaths, distributed in 213 countries and territories, reached more than 538 million and 6.3 million by June 22, 2022, respectively. As of the publication date of this article numbers are still going up worldwide, even in those countries best prepared to deal with a pandemic, according to the 2019 Global Health Security Index, which measures health security and related capabilities with regard to epidemic prevention, early detection for epidemics, rapid mitigation of epidemic spread, the presence of a robust health system to treat the sick, compliance with international norms, and country vulnerability to epidemics (10). In addition, although the pandemic was generally contained in China during March–April 2020, localized outbreaks of COVID-19 have emerged from time to time since June 2020, some of which were due to the influx of contaminated meat and seafood from abroad (e.g., in early July 2020, Chinese customs found traces of SARS-CoV-2 on shrimp packaging from Ecuador at Dalian and Xiamen ports). Such incidents have raised concerns about imports of frozen products and the inadequacy of monitoring only traveler flows (94). Moreover, the emerging SARS-CoV-2 variants occurring first in the United Kingdom and India have also been exported to many other countries via air travel. All these lessons learned from COVID-19 imply that the current global networks of NNDRSs need to be innovated in all countries to better protect one another in the inseparably intertwined larger international network.

Although early identification and prediction of future disease trends may be technically feasible, more work is needed to improve accuracy so that policy makers can use these predictions to guide prevention and control efforts, as described in a recent call motivated by COVID-19 for China to upgrade its current NNDRS (34). This article consists of four sections. In the first two sections, we review the advantages and limitations of the current NNDRS in most, if not all, countries. In the third section, we discuss some lessons learned about prevention and control from the first wave of COVID-19. In the last section, we describe some technological innovations in public health surveillance, including information technology, data science, and the digital twin method.

MAJOR ADVANTAGES OF THE NNDRS

In most countries, the NNDRS is a passive surveillance system that collects information on infectious diseases and usually has a built-in geographic information system (GIS) to visualize spatial information of reported disease cases and plot their clusters to support areal-level analysis for infectious disease outbreaks. Countries have been moving toward electronic reporting through the NNDRS, which has improved timeliness. Although the current global networks of NNDRSs have

Table 1 Advantages and limitations of the national notifiable disease reporting systems (NNDRS) in the ten countries best prepared to deal with a pandemic, according to the 2019 Global Health Security Index (from high to low)

Countries	NNDRS	Advantages	Limitations
United States	NBS, NNDSS, NORS	NBS: ■ Reduced time of reporting diseases ■ Receiving more laboratory reports ■ Improved communication among local, state, and federal public health staff ■ Ability to push data entry back to the sources ■ Reduced paper-based reporting ■ Robust reporting modules	NNDSS: ■ Differential management of the NNDSS across states ■ Lack of epidemiological data exchange across different levels of the CDC without building extra infrastructure ■ Poor communication and coordination among different levels of the CDC ■ Poor communication and coordination among the electronic medical records and case reporting systems of different levels of public health sectors NORS: ■ Voluntary reporting standards for diseases ■ A small proportion of cases related to outbreaks ■ Unknown ability to reflect the same sources of infection and settings of sporadic diseases ■ Unreported outbreaks on cruise ships at the international ports and outside the United States
United Kingdom	NOIDS	■ Electronic notification of diseases with an electronic signature for authorization of general practitioners ■ Reduced delay through computerization of storage and retrieval of data	■ Lack of epidemiological information at a regional level ■ Many manually performed functions
The Netherlands	Osiris	■ Emphasizing the concept of one health ■ Inclusion of the first Center for One Health worldwide ■ Focusing on syndromic surveillance	■ A risk of overlooking an outbreak ■ Missing complete notification data
Australia	NNDSS	■ Reduced time of reporting diseases to jurisdictional notification (from fortnightly to daily) ■ Reduced time of data upload from jurisdictions to NNDSS (from fortnightly to daily)	■ Lack of epidemiological data exchange across different levels of the CDC without building extra infrastructure ■ Poor communication and coordination among different levels of the CDC ■ Fragmentation of data collection and incompatible notifiable disease databases

(*Continued*)

Table 1 (*Continued*)

Countries	NNDRS	Advantages	Limitations
Canada	CNDSS, GPHIN	CNDSS: ■ Improved interactivity of the Web-based system ■ Provides open data on all 56 notifiable diseases GPHIN: ■ A high-performing distributed system that can afford the big data ■ Integration of multisource public health information ■ Timely reporting of infectious diseases	CNDSS: ■ Voluntary reporting standards for diseases GPHIN: ■ Limited scalability due to the unavailable knowledge sources ■ Unverified and differential data compared with the true reported cases ■ Limited data sources from media in English or French only ■ Inaccurate data from media in other languages
Thailand	NADSS, National Surveillance System	NADSS: ■ Annual sero-surveillance in dairy cattle ■ Enhanced veterinary capability in the early warning system ■ Compliance with the WOAH international animal health codes ■ Screening for transboundary animals	National Surveillance System: ■ Voluntary reporting standards for diseases ■ Varied reporting methods and requirements over time
Sweden	SmiNet	■ Easy data collection based on the Internet-based forms ■ Readily accessible, cost-effective, and scalable ■ Timely data flows ■ Full integration of clinical and laboratory notification ■ High performance in handling more than 50 diseases	■ Not being able to cover the entire population ■ No laboratory testing included ■ Need for recruiting and maintaining participants
Denmark	Danish surveillance registry	■ High data quality ■ General population surveillance	■ Extensive efforts in comparing and validating the same information/data from multiple registries ■ Completeness of the diagnosis (relative to the general population) depends on whether the condition requires hospitalization and on diagnostic and coding practices ■ Less supervised registry enrollment and bias for registries due to missing or incomplete data ■ Extensive and constant financial support needed for implementation, operation, and maintenance of the system

(*Continued*)

Table 1 ***(Continued)***

Countries	NNDRS	Advantages	Limitations
South Korea	NNDSS, Disease Web Statistics System	NNDSS: ■ Timely reporting The Disease Web Statistics System: ■ Standardized and informative reporting of the national notifiable diseases, including diagnostics and epidemiological information of each infectious disease ■ Data sharing with health care agencies	NNDSS: ■ Time lag in diagnosis ■ Delayed reporting by doctors ■ Weak public education and clinical guidelines The Disease Web Statistics System: ■ Voluntary reporting standards for diseases
Finland	FNIDR	■ Whole population surveillance ■ Saving manpower in the laboratory-based notification through automated computer algorithms	■ Inconsistencies in the information systems of different service providers ■ High challenge in data sharing due to lack of integration across different information systems ■ Data updates on an annual or monthly (rather than weekly or daily) basis

Abbreviations: CDC, Centers for Disease Control and Prevention; CNDSS, Canadian Notifiable Disease Surveillance System; FNIDR, Finnish National Infectious Diseases Register; GPHIN, Global Public Health Intelligence Network; NADSS, National Animal Disease Surveillance System; NBS, National Electronic Disease Surveillance System Base System; NNDRS, National Notifiable Diseases Reporting System; NNDSS, National Notifiable Diseases Surveillance System; NOIDS, Notifications of Infectious Diseases; NORS, National Outbreak Reporting System; WOAH, World Organization for Animal Health.

not performed adequately in preventing and controlling COVID-19, many of these systems have important advantages (**Table 1**).

The NNDRS has at least three advantages compared with the early paper-based disease reporting systems. First, data collection of infectious disease cases has been simplified. For example, prior to the NNDRS, district/county-level disease cases were aggregated and reported by mail only to the upper-level Center(s) for Disease Control and Prevention (CDC) in China (i.e., the municipal/prefecture CDC) and then to the provincial CDC and finally to the national CDC. The NNDRS changed this operational mechanism in 2004 by enabling electronic reporting of individual cases from all hospitals and primary health care clinics directly to the national CDC. Second, the timeliness of reporting has been substantially improved, which could assist in forecasting disease outbreaks and designing control strategies. For example, the National Electronic Disease Surveillance System Base System (NBS), developed by the US CDC in 2002, has collected more than 700,000 notifiable disease cases and provided timely information for the US CDC to use in making decisions in response to public health emergencies (12). This advantage has also been observed in other countries, including the NNDRS in China (33), the National Notifiable Disease Surveillance System (NNDSS) in Australia (3), the NNDSS in South Korea (91), and the National Epidemiological Surveillance of Infectious Diseases in Japan (58), where the times of updates, data analyses, and communication on diagnostics of the reported cases have been reduced from time periods of, e.g., 1–2 weeks, to a daily basis. Third, disease surveillance has been more cost-effective as case collection and reporting have been digitalized and the surveillance of multiple infectious diseases can be managed in one system (12).

The data quality and reliability of the NNDRS have been improved by distributed computing technology, high standards for constructing disease databases, and the scalability of disease surveillance systems. For instance, the Danish surveillance registry is of high data quality and is often used in connection with research projects because the system can automatically check data completeness and accuracy from multiple registries (65, 74, 77); with systematic and hierarchical reporting and disseminating mechanisms, the national integrated surveillance system in Italy enables investigators to predict the burden of disease and incidence trends for each hepatitis type on the basis of complete case data, including serological testing results, sociodemographic characteristics, geographic location, incidence rate, and information on risk factors (78). In addition, the inclusion of a "one health" component, focusing on the human–animal–environment disease interface (30), in the NNDRS has improved the robustness of the NNDRS in facing emerging infectious diseases and has strengthened the ability to investigate the emerging sources of infectious diseases. About 60.3% of the emerging infectious diseases reported during 1940–2004 belonged to zoonotic diseases, 71.3% of which, including COVID-19, originated in wildlife (36). Hence, the one health approach is extremely important for the early warning of future epidemics (10), which has been initially realized in some countries. For example, the Netherlands Center for One Health was established to report the potential zoonotic threat monthly to the Dutch National Institute for Public Health and the Environment Center for Infectious Disease Control (20, 80).

MAIN LIMITATIONS OF THE NNDRS

Despite the aforementioned advantages, several limitations to NNDRSs across the world contributed to the heavy loss of lives due to COVID-19 globally. First, NNDRSs, on average, are insufficiently timely. The current NNDRSs in most countries have at best a built-in, perhaps sometimes Web-based, GIS for real-time visualization of spatiotemporal dimensions of diseases and epidemics, e.g., temporal trends and/or geographical distribution of disease cases. This approach, however, is still considered retrospective due to the inherent time lag in case reporting and thus is insufficient to presciently and robustly identify early risk and issue early warnings for public health emergencies. Moreover, as of 2019, only 32% of all countries had an interoperable electronic real-time communicable disease surveillance system, and only about 11% of African countries were considered to have acceptable real-time surveillance and reporting systems (10); the WHO emphasized the need for preparedness for COVID-19 in African countries at the beginning of the pandemic due to their vulnerable public health surveillance systems. This problem and the subsequent reporting issues have partly accounted for the underestimation of epidemics by governments in both developed and developing countries (in either participant-based or health care–based reporting systems), such as the National Outbreak Reporting System (NORS) in the United States (**https://www.cdc.gov/nors/data/using-nors.html**), the NNDSS in Canada (73), the National Electronic Surveillance System (SmiNet-1) in Sweden (85), the National Surveillance System in Thailand (48), and the Disease Web Statistics System in South Korea (59).

Second, communication and coordination among different levels of the CDCs within countries are insufficient. Race/ethnicity concerns (15), privacy (53), and ethical issues (39) are primary challenges to inhibiting data sharing across surveillance systems at different levels. This lack of data sharing has hindered our ability to understand the epidemic trend, which usually varies at different geographic scales and across countries worldwide. Technical barriers, manifested in the incompatibility and standardization issues for data coming from different electronic health record (EHR) systems and the lack of process interoperability in health care systems, have also hindered effective data sharing across clinical and public health fields (1, 26, 42). For example, the NNDRS could not exchange epidemiological data across CDCs at different levels without building extra infrastructure for data exchange, such as in the United States, Australia, Germany (3), and the United Kingdom (13). The direct influences of these phenomena included the fragmentation of data collection and the incompatible notifiable disease databases, which could hinder accurate monitoring of epidemiological data on epidemics. This problem has also been highlighted in the 2014 Australian National Framework for Communicable Disease Control (2). In the United States, multijurisdictional and multihierarchical data sharing across different states has been facing legal barriers because state disease reporting laws prevent the sharing of personally identifiable health information across jurisdictions (37). The United States has three communicable disease surveillance systems: NORS, NBS, and NNDSS. However, it is difficult to obtain uniform epidemiological data from the US CDC; this was especially true during COVID-19. Therefore, data-sharing protocols or agreements between states and countries may also create barriers to fully utilizing state-level data in surveillance systems at different hierarchies (15). In addition, data sharing across countries faces even more technical, motivational, economic, political, legal, and ethical challenges than data sharing across jurisdictions in one country (49, 79).

Third, all existing early-warning systems require ongoing monitoring and evaluation. This need was made apparent when these systems failed to identify the COVID-19 outbreak at the early phase. Although countries including the Netherlands and China have taken steps toward early notification of emerging infectious disease outbreaks [e.g., the Dutch legislation and the Chinese pneumonia surveillance system (80)], the ongoing lack of clarity regarding standards for notification and hence the underreporting of issues limit their capacity to prevent emerging infectious disease outbreaks. Also, although the Dutch early-warning system, which relies on expert opinions, has functioned well because the number of outbreaks has been limited and communication lines between governments and medical professionals are short, there is always a risk of overlooking disease outbreaks when the number of outbreaks increases, such as with COVID-19 (80). Syndromic surveillance has been proposed as an investigational approach that uses symptom and/or preliminary diagnosis information and rapid data collection methods to provide information for public health action in a more timely manner than other more traditional approaches. However, several challenges prevent its ability to function fully, such as difficulties in defining optimal data sources, evaluating appropriate syndromic definitions, and developing minimally acceptable response protocols. Given the intrinsic trade-offs among timeliness, sensitivity, and false alarm rate (72), as well as concerns for privacy and possible public panic, relevant agencies and governments remain conservative in deploying personnel and financial resources to implement syndromic surveillance and hesitate to activate it if it exists (5, 72). Another challenge is differentiating emerging infectious diseases from other known diseases with similar symptoms, when using generic respiratory syndromic indicators, such as those used to distinguish COVID-19 from influenza (18). Moreover, syndromic surveillance cannot identify asymptomatic cases.

Fourth, all existing NNDRSs lack a strong module that focuses on the linkage among human, animal, and environmental data. For instance, data on human, animal, and wildlife surveillance can be shared across different ministries in only 30% of all countries, with a lack of data-sharing mechanisms in other countries (10). Interoperability, convergent integration, semantic consistency, and interconnectivity are four primary mechanisms of integration between human and animal health surveillance systems (21).

Fifth, epidemiological data are still disconnected from real-time laboratory data. About 77% of all countries lack the ability to collect ongoing or real-time laboratory data (10). In the other 23% of countries, this procedure should be expedited by modern technologies to prevent the spread of highly transmissible diseases, such as COVID-19, which has advanced the rapid synchronization of NNDRSs and laboratory data (83). However, due to the requirements for technological capability (genome sequencing for mutant tracing), the significant financial investment needed to acquire necessary equipment (e.g., RT-PCT machine), and the advanced knowledge and personnel needed for processing and integrating epidemiological and laboratory data, the real-time connection of epidemiological data and laboratory data remains very challenging even in developed countries, not to mention in less developed countries (45, 57).

Finally, the capacity for small area estimation (SAE), i.e., estimating parameters in small geographical areas or in small subpopulations of interest (with few or no available samples) included in a larger survey, is still limited in many NNDRSs. This lack of capacity limits the opportunity to quickly investigate disease patterns in a small geographic area or subpopulation. A small-area surveillance module using the SAE approach should be integrated with the NNDRS, which can easily collect data (e.g., case reports) and conduct modeling (e.g., Bayesian spatial models) at any small geographic scale, carry out the accuracy assessment of SAE, and disseminate SAE results to policy makers and the public (81, 95). Such small-area surveillance modules enable public health agencies to identify spatiotemporal patterns of infectious diseases at a local geographic level, investigate the underlying reasons, and implement precision containment strategies accordingly (e.g., defining the extent of lockdown and supply of vaccines) (43).

LESSONS ABOUT PREVENTION AND CONTROL FROM THE FIRST WAVE OF COVID-19

Early Case Identification

Early case identification is key to controlling and mitigating an epidemic. Detection capacity is largely a function of well-funded public health surveillance programs integrated with robust health care systems. Recent technological developments, such as EHRs, GIS, and the analytic capacity for real-time monitoring, can play key roles in quickly identifying new cases and deploying appropriate responses (e.g., contact tracing). Vertical integration of the public health capacity, from country level to community and hospital levels, is also critical as successful early case identification relies on not only local communities but also the data-linkage capacity from local to regional and national surveillance. For example, in the United States, hospital systems often have rapid high-quality data; however, these do not connect well to the public health surveillance infrastructure. Although the United Kingdom has extensively used EHRs to help support COVID-19 surveillance and containment, fewer efforts have been made to establish centralized data collection, integrate validation mechanisms across the linked EHRs, and implement rapid synchronization mechanisms with NNDRSs because this work is time-consuming and resource-intensive (86). Lacking such efforts may have caused selection bias and over- or under-interpretation of relevant findings and therefore significantly lowered the value of EHRs in informing NNDRSs (9).

Testing and Tracing Capacity

In addition to early detection, countries that were able to rapidly deploy intense testing capacities fared better during the COVID-19 pandemic (89). Many countries experienced significant delays in their expansion of testing capabilities for various reasons, including poorly planned infrastructure, disruptions in supply chains (e.g., for testing reagents), and slow policy response. The implementation of contact tracing, which is typically effective yet highly labor-intensive, has varied considerably by country. In addition, many countries or jurisdictions may have had the capacity to collect testing and tracing data at large scales and even isolate close contacts, but they did not have the capacity to analyze the epidemiological patterns of testing and tracing data.

Capacity to Implement Required Public Health Policies

During the COVID-19 pandemic, a given country's response capacity has been strongly linked to the roles, responsibilities, and structural components of its public health agencies. Overall, countries with a history of strong public health investments and experience in managing interventions successfully reacted not only more quickly, but also more effectively and were better prepared to enact traditional outbreak response strategies, including isolation, quarantine, social distancing, and community containment (84, 88). Networks and international collaboration have been improving, with lessons learned from previous epidemics such as severe acute respiratory syndrome (SARS) and with structures such as the Global Outbreak Alert and Response Network (GOARN). Data-sharing consortiums, such as GISAID (54), have also been playing an increasingly important role in the rapid sharing of information and strategies.

Country-Wide Practice and Policy Response

The impacts of COVID-19 have highlighted the importance of resilience planning, which could ensure that systemic impacts from pandemics and other natural or human-made disasters are minimized in terms of scope and severity, especially with regard to vulnerable populations. The observed differences in COVID-19 impacts among countries have highlighted the shortcomings of respective country-level institutions in terms of public health surveillance, organization, and health care capacity and more broadly across economic, social, and environmental factors. Although international comparisons are not straightforward, there have been marked variations in government readiness and the ability or willingness to take decisive and comprehensive action to stave off the worst effects of the pandemic. Germany and South Korea performed relatively well, quickly expanding their testing and tracing capabilities. By contrast, the United Kingdom, the United States, and Brazil, among others, were slow to react and haphazard in the policies they adopted. This approach was reflected in delays in enacting lockdown procedures, severe shortfalls in testing and tracing, low stocks of personal protective equipment, and confusion in terms of public health communication. These serious deficiencies in pandemic planning and response sparked protests and have often been accompanied by poor transparency and resistance to accountability (for instance, no major policy makers in any of the three countries mentioned above have been removed from their positions) (41).

Systems Thinking to Drive Holistic Public Health Surveillance

While health emergency response has relied primarily on the health sector (e.g., public health surveillance, public health agencies, and health care organizations), some epidemic containment policies, such as lockdowns during the COVID-19 pandemic, have had major and ongoing social, economic, environmental, and behavioral impacts (29, 35, 51, 92, 93). Systems thinking is required to gain a holistic understanding of those impacts because of the complex links and interactions among multiple domains by arranging a set of interacting and interdependent elements that function as a whole, producing what individual constituents cannot produce (50, 52, 61). Systems thinking offers a paradigm of understanding health as a structured system exhibiting dynamic complexity over time within certain contexts. In the design and operation of public health surveillance, systems thinking can (*a*) help stakeholders understand how disease spreads as people interact with each other and their contexts within social networks; (*b*) encourage people to transcend disciplines and organizations to pursue understanding of more complicated health system challenges from multiple angles; (*c*) conceptualize structure design of new surveillance systems and strategize major changes to better cope with public health challenges; (*d*) guide the design of infrastructure to promote seamless connections among EHR systems, national-level lab databases, and surveillance systems at national and local levels; and (*e*) facilitate coordination and communication among lab, clinical, hospital, surveillance, public advising, and public health administration teams (17, 44). Such approaches can provide leverage points for interventions and have shown potential for addressing inequalities (27, 64). The COVID-19 pandemic has highlighted the need for reforms and improvements to the capacity of both global and national public health governance,

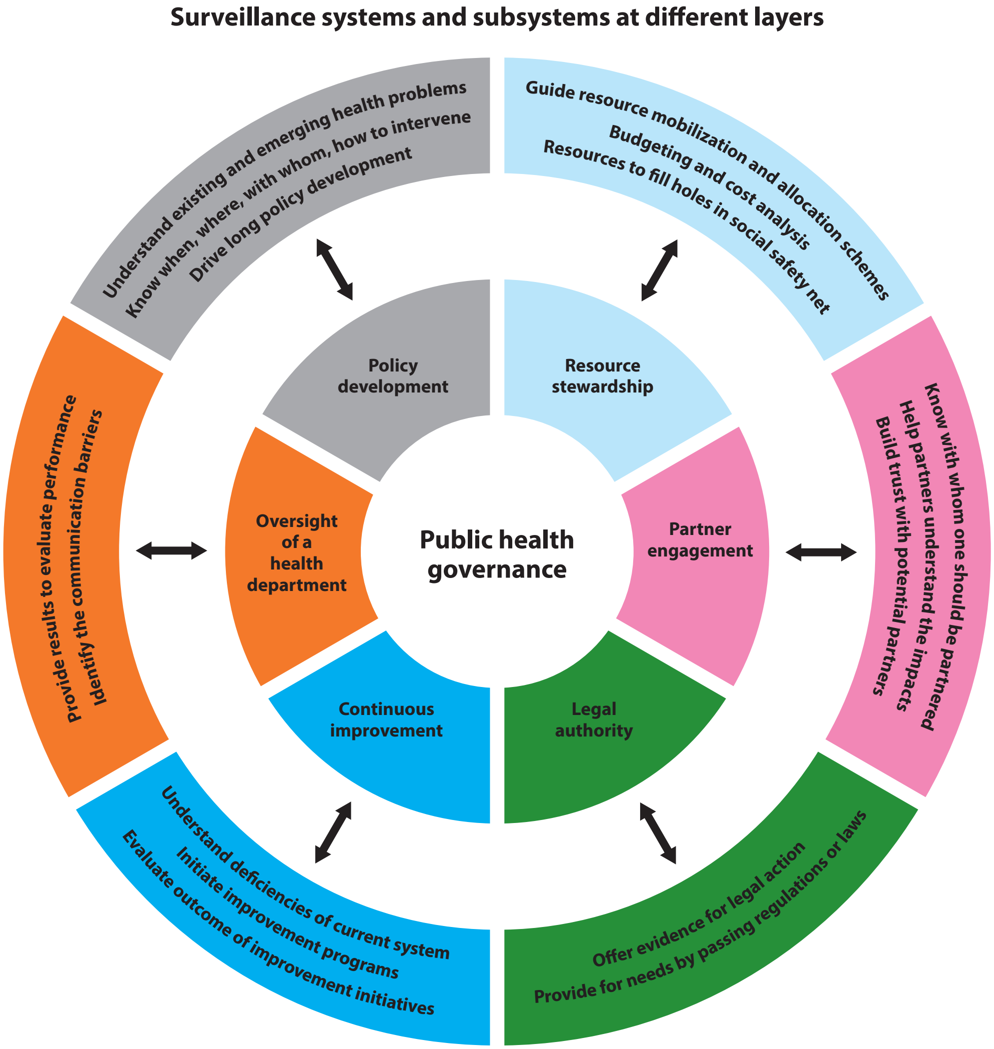

Figure 1

Ideal relationships between public health governance (inner sectors) and surveillance systems (outer sectors).

of which the six core functions are policy development, resource stewardship, continuous improvement, partner engagement, legal authority, and oversight of a health department (**Figure 1**) (12). Achieving efficient and equitable responses and containment strategies also requires improved multilevel collaboration at the global, regional, national, and local levels, particularly with respect to data sharing (24). As shown during the COVID-19 crisis, governance and leadership capacity, along with multilevel coordination, are essential to the strategic deployment of health care resources and the effective mobilization of individuals and communities in pandemic containment (**Figure 2**).

These reforms can shore up system resilience and preparedness, at multiple levels, for pandemics. At its core, control of the COVID-19 pandemic has depended on adequate infrastructure and processes for disease tracking: diagnostics, case identification, and contact tracing. This

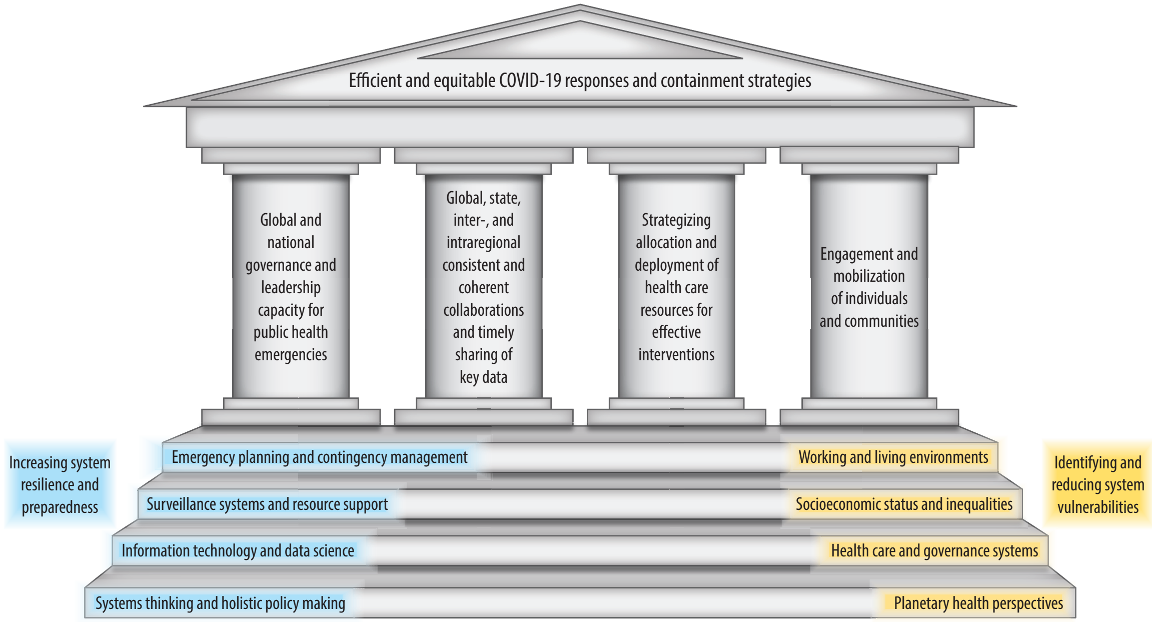

Figure 2

Schematic representation of a systems thinking approach for efficient and equitable COVID-19 responses and containment strategies.

capacity must be supported by a strong public health system that has leveraged other sectors of society through health in all policies (HiAP), which is a collaborative approach that integrates and articulates health considerations into policy making across sectors to improve the health of all communities and people. HiAP recognizes that health is created by a multitude of factors beyond health care and, in many cases, beyond the scope of traditional public health activities (11). In turn, a comprehensive public health response relies on systems thinking, which not only points toward the upstream structural and social determinants of health but also allows for the integration of feedback loops and the consideration of emergent properties.

The tightly coupled elements of interest in public health surveillance (e.g., pathogen, microbial genetic mutation, human socioeconomic activities) demonstrate spatiotemporal dynamics, and their relationships exhibit obvious system properties of adaptive self-organization, being governed by feedback, nonlinearity between effects and actions, historic path dependency, and counterintuitiveness. These features render it barely possible to use traditional methods to conduct public health surveillance. Systems thinking can harness system theories to drive the strategic blueprint and architectural design for a sustainable public health surveillance system, which defines various functions, processes, policies/interventions, governance, and resources required for development and deployment (17, 38, 44, 55, 62). By drawing on system simulation tools, such as system dynamics, agent-based simulation, social network analysis, or any combination thereof (i.e., hybrid models) (7), systems thinking can equip decision makers and policy makers with some pivotal skills, such as performing root cause analyses for problems of interest, scrutinizing critical areas for investigation, conducting system design and refinement, preventing policy backfiring by designing and implementing high-leverage interventions, and enhancing continued learning and improvement from past pandemics (25, 50, 52, 63). Systems thinking also enables a smooth transition of the data and findings from surveillance systems to the planning, implementation, and evaluation of public health action and provides feedback and guidance on data collection (56).

TECHNOLOGICAL INNOVATIONS IN PUBLIC HEALTH SURVEILLANCE

Information Technology and Data Science

In the early stage of COVID-19 in China, a significant drop in new infections would not have happened in such a short term without the collaborative efforts of many location-aware service providers (i.e., services that provide targeted information to individuals based on their geographic location in real time, such as maps, navigation, and tracing services). Since January 2020, the Chinese mobile phone service providers have been collaborating with the National Health Commission of China, the China CDC, and other relevant governmental sectors and agencies to analyze moving trajectories of COVID-19 cases and their close contacts by cross-referencing location data from multiple sources, including mobile phone service providers, transportation, business transactions (online/offline), resident community screening, neighborhood watch, and social media data (**Figure 3**). China was the first country to develop and put into practice COVID-19-specific apps for tracing and surveillance, with privacy secured (70). Doing so has supplemented the traditional epidemiological survey data by accurately describing the travel history, including daily trajectories, of those infected or those with suspected illness so that close contacts on their trajectories could be identified and notified quickly for self-monitoring and/or isolation from their families to avoid infection being spread. This approach has demonstrated the important emerging roles of information technology and big data in epidemic control and prevention. For example, flight-booking data and intercity human mobility data have been used to estimate the spread of COVID-19 (40, 87); smartphone-based tracing data and social media data have been used to understand spreading mechanisms and predict pandemic trends (46, 47, 66, 82). Combining epidemiological surveys with app-based tracing and derived geo-information has helped to strengthen spatial data infrastructure for infectious surveillance systems and minimize the impact of COVID-19 (67, 71, 97).

Despite significant technological progress, the theories and practices of infectious disease epidemiology and public health surveillance have struggled to keep pace with the changing nature of epidemics and pandemics in the twenty-first century (4). As mentioned above, testing and contact tracing are cornerstones of timely and effective response. While much has been said and written about big data and the development of artificial intelligence, data infrastructure has room for improvement in terms of the timely collection and analysis of cases and related social determinants. Information technology and surveillance systems could harness these new technologies to track not only infections, but also social, economic, and environmental living conditions to address inequalities in risk (96). The rapid development of location-based technologies, including GIS-facilitated data collection, analysis, and visualization, has made important contributions to both global and local action (28, 34, 90). Remote sensing, featuring the simultaneous data acquisition capacity over a large region and a short revisit time over the same location on Earth, can monitor the impact of environmental changes (e.g., global warming) on infectious disease risk (31, 32). Such big data unbounded by administrative boundaries could also drive estimation beyond administrative boundaries. In addition, in the future, lab test results and contact tracing data can be further integrated through mobile devices, which could address test result deduplication issues by, for example, linking together all lab results on the same person over time and across systems, making contact tracing more effective. However, data-driven decision-making is only as comprehensive as the data or evidence it contains. Therefore, the means by which and extent to which such

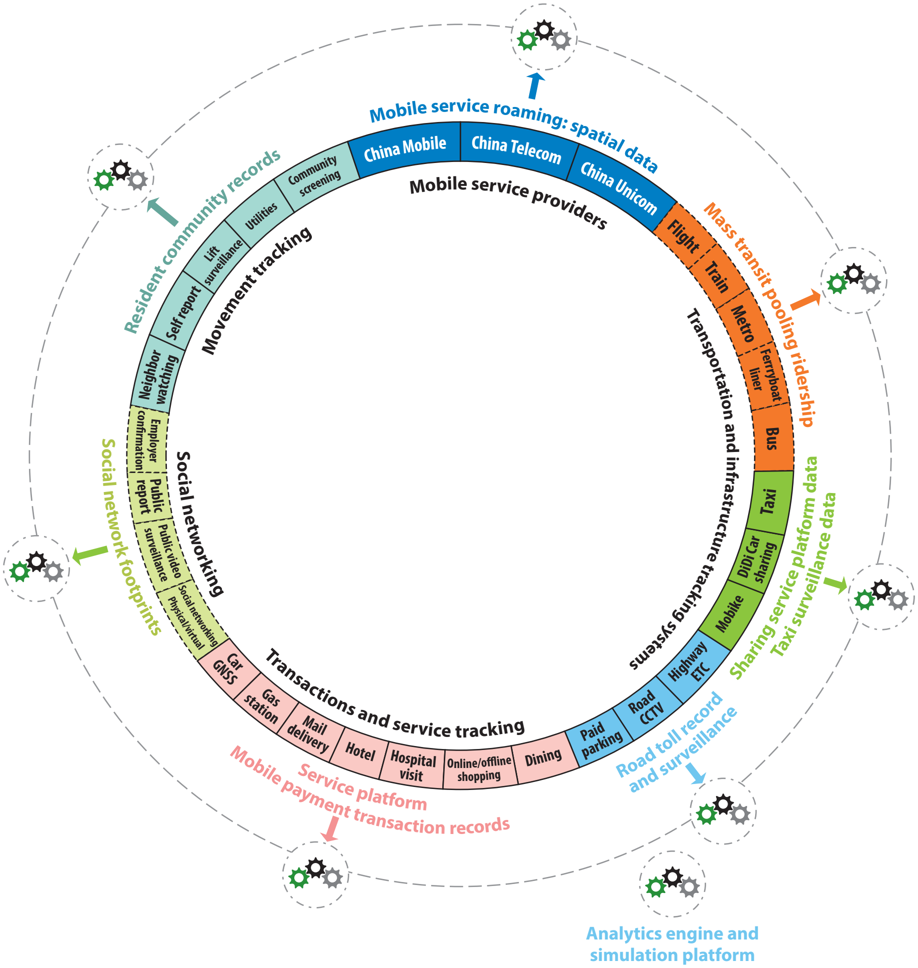

Figure 3

Digital twin used for tracking dynamic risk for the COVID-19 pandemic. Abbreviations: CCTV, closed-circuit television; ETC, electronic toll collection; GNSS, global navigation satellite systems.

technologies are applied are likely to be highly context specific and, in many cases, may even be difficult to adopt because of concerns regarding individual privacy.

The systematic monitoring of interventions, and people's perception, attitudes, daily movements, social interactions, and physical and mental health, can provide valuable insights to guide future actions. Thus, the variability in COVID-19 contexts and response policies presents many opportunities for natural experiments (76). Such underutilized opportunities call for improved population-based longitudinal studies that assess both structural determinants of health as well as individual behavior and health outcomes over time. Location-based technologies and other smartphone-embedded sensors, along with online questionnaire platforms, can help collect such data (which include hard-to-reach populations). Corresponding data infrastructures with near real-time treatment capabilities can provide critical indicators for decision makers. Data privacy issues and other ethical and political challenges relating to the representation of private information in data systems must be transparently and comprehensively addressed to make such efforts acceptable. Several initiatives are positively contributing to these discussions, including the Global Alliance for Genomics and Health (68) and the Montreal Declaration for Responsible Development of Artificial Intelligence (14). The resulting protocols and policies will be valuable resources for future resilience planning.

Digital Twin: A Robust Tool to Respond to Public Health Emergency Events

Digital twin is the virtual replica of a physical entity or system across its life course and uses real-time big data and other sources to enable visualizing, learning, reasoning, and dynamic recalibration for precision interventions (6, 22). With the acceleration of development in the internet of things—cloud computing, artificial intelligence, big data analytic engines, complex system simulation platforms, and augmented, virtual, and mixed reality—digital twin is witnessing rapid deployment in different industries (16, 19). For example, researchers and engineers in the life science and health care sectors have been exploring the potential applications of integrating genotype and phenotype data with the digital twin to help to develop personalized medicine (60, 69). More examples include in silico genome and digital twins of the human heart and brain, medical equipment, emergency departments, and hospitals (**Figure 4**) (16, 69).

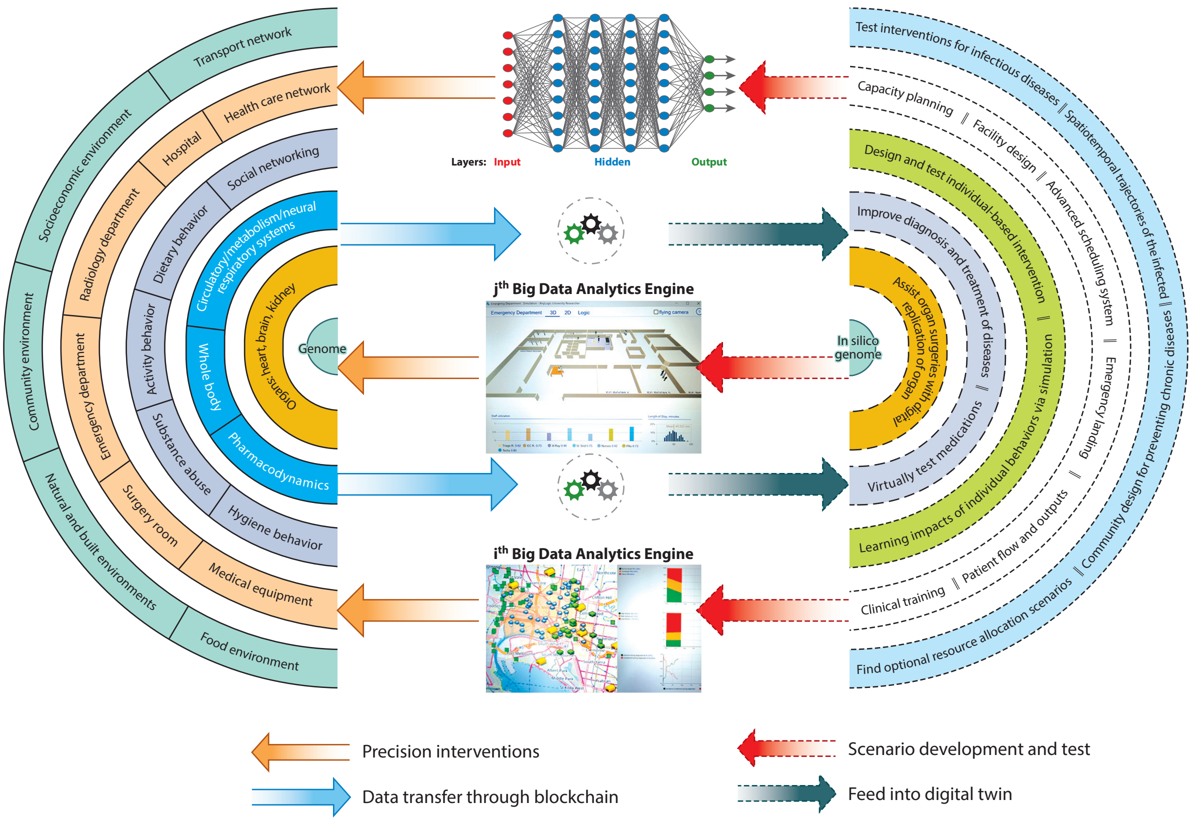

Figure 4

Applications of artificial intelligence, information technology, data science, and digital twin in health care and life science domains. The solid lines that compose the left side semi-circles denote the physical world, and the dashed lines that compose the right side semi-circles denote its corresponding digital twin (i.e., the virtual world).

Digital twin could play important roles at different phases of COVID-19 if its full-fledged potential in public health emergency events is realized. For example, discrete event simulation, agent-based simulation, and virtual reality technologies could be used together to detect flaws in the design of quickly constructed field or cabin hospitals, which may compromise their effectiveness, such as when used for quarantine. Combining internet of things and virtual reality technologies enables health professionals to practice patient care and complicated surgeries ahead of time, which could prevent medical staff from becoming infected while being exposed to patients with extremely high viral loads. By using hybrid models that integrate GIS, agent-based modeling, and social network analysis, researchers could quickly evaluate the spread of infectious diseases and the effectiveness and efficiency of various containment strategies while considering the infrastructure deployment, transport networks and schedules, and individual mobility patterns in virtual reality.

Several concerns exist when applying digital twin. Privacy safety is a major one because this approach involves an intrusive collection of individual location data, which can raise additional ethical issues, such as discrimination (8). Data propriety may also become a concern because agencies might use these data for commercial or other illegal purposes, which can present a risk to regulatory compliance. The vulnerability of the system to hacking and virus attacks is a long-term technical concern, which can result in consequences similar to those from ethical violations. Another concern is how the digital twin is operated: The centralized operation may render the managing agencies as a superpower in terms of controlling citizens' data, while the decentralized operation may significantly reduce the interoperability of different data source

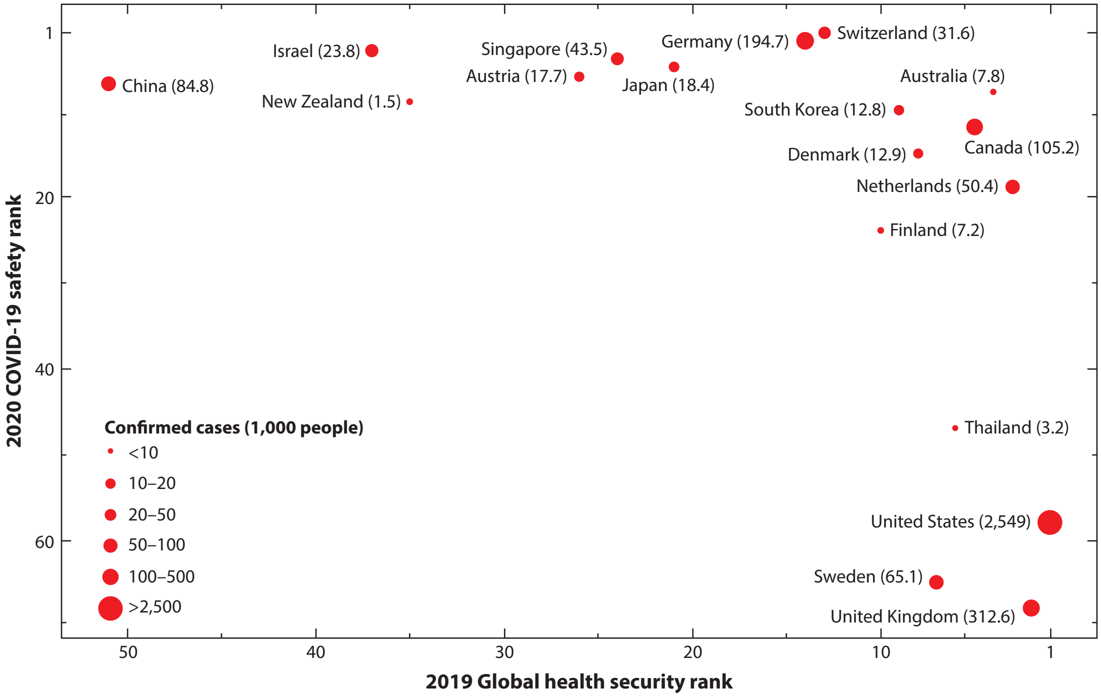

Figure 5

Comparison of the top 10 countries in the 2019 and 2020 health safety rankings (the number in parentheses after each country multiplied by 1,000 is equal to the total number of confirmed COVID-19 infections by June 28, 2020).

providers. However, such privacy-related concerns could be addressed by properly employing new technologies, such as blockchain. Given that digital twin can aid in identifying the vulnerabilities in public health systems and exercise a new way of improving personalized and population health, we suggest that regulations in all countries need to be put in place to ensure that digital twin can be deployed during public health emergencies.

CONCLUDING REMARKS

All the limitations of the current NNDRSs may have hindered the ability to detect the COVID-19 pandemic at the early stage. Even Spain and the United Kingdom, which scored best in terms of real-time public health surveillance and reporting, could not have prevented themselves from becoming the European epicenters of the COVID-19 pandemic. According to the recently published 2020 safety rankings through the months of the pandemic, there have been significant changes in the rankings among countries. These rankings were scored on the basis of quarantine efficiency, monitoring and detection, health readiness, and government efficiency: All countries ranked in the top 10 in 2019 had degraded, with only Australia and South Korea staying at the bottom of the top-10 list in 2020 (**Figure 5**). These findings imply that the ongoing NNDRSs in most if not all countries have not been adequately prepared for pandemic forecasting (10). Technology-driven innovative public health surveillance systems are expected to improve the timeliness, completeness, and accuracy of case reporting during outbreaks and should also enhance feedback and transparency, such that all stakeholders, from public health authorities to the general public, should receive actionable information on infection control and disease risk mitigation earlier than ever before. All epidemic information in one country should consistently stem from one intelligent, robust NNDRS, which should eventually be developed into one global intelligent disease surveillance and reporting system to protect everyone in the world equally.

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