Public Health Disease Surveillance Networks

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ABSTRACT Zoonotic infections are important sources of human disease; most known emerging infections are zoonotic (e.g., HIV, Ebola virus, severe acute respiratory syndrome, Nipah virus, and enteropathogenic *Escherichia coli*) and originated as natural infections of other species that acquired opportunities to come in contact with humans. There are also serious infectious diseases classically considered zoonotic, such as influenza, rabies, bubonic plague, brucellosis, and leptospirosis. More recently, it has been recognized that wildlife constitutes a particularly important source of novel zoonoses. With all this microbial movement, surveillance is considered the first line of public health defense. The zoonotic origin of many human and livestock infections argues strongly for the synergistic value of a One Health approach, which provides the capability to identify pathogens crossing into new species and could provide earlier warning of potential epidemics. This article discusses public health surveillance and major recent surveillance initiatives and reviews progress toward implementing a One Health surveillance framework. Networks discussed include global intergovernmental organizations and recent combined efforts of these organizations; Web-based nongovernmental systems (e.g., ProMED, the Program for Monitoring Emerging Diseases); and networks of bilateral or multilateral government programs (e.g., the CDC's Global Disease Detection [GDD] platform; the U.S. Department of Defense's Global Emerging Infections Surveillance and Response System [GEIS]; regional and subregional networks; and the U.S. Agency for International Development's Emerging Pandemic Threats [EPT] program and its surveillance component, PREDICT). Syndromic surveillance also has potential to complement existing systems. New technologies are enabling revolutionary capabilities for global surveillance, but in addition to serious technical needs, both sustainability and data-sharing mechanisms remain challenges.

INTRODUCTION

Zoonotic infections are important sources of human disease. The great majority of emerging infections identified to date (including HIV, Ebola virus, severe acute respiratory syndrome [SARS], Nipah virus, and enteropathogenic *Escherichia coli*) are zoonotic ([48]). These diseases originate as natural infections of other species that are given opportunities to cross the animal-human interface and come in contact with humans ([1]–[4], [49]). Wildlife constitutes a particularly important source ([2]).

Infectious disease emergence and spread are likely to continue and increase, as drivers such as agriculture, land use change, urbanization, and globalization proceed apace ([3]). Surveillance is considered the first line of defense for public health ([5], [6]), and the zoonotic origin of many human infections argues strongly for the synergistic value of a One Health approach ([7]) to surveillance, which provides the capability to identify pathogens crossing animal-human interfaces and can provide earlier warning of new epidemics waiting in the wings ([3]). Such knowledge can be used to focus efforts to prevent microbial traffic across animal-human interfaces and thereby reduce the risk of emerging infections. This article gives an overview of public health surveillance and some major existing surveillance networks and reviews progress toward implementing a One Health framework.

WHAT IS PUBLIC HEALTH SURVEILLANCE?

Today, we take for granted the idea of disease surveillance, but the concept as we now know it was formulated in the mid-20th century by Alexander Langmuir at the CDC (the agency was then called the Communicable Disease Center; it is now the Centers for Disease Control and Prevention). Previously, surveillance usually meant observing individuals clinically for disease. Langmuir redefined it to mean identifying and enumerating diseases in populations, as a public health tool ([8]). Stephen Thacker and Ruth Berkelman at the CDC subsequently suggested the term "public health surveillance" for greater clarity ([9]). The formal definition currently used by the CDC ([10]) is widely accepted and often quoted: "Public health surveillance is the ongoing, systematic collection, analysis, interpretation, and dissemination of data regarding a health-related event for use in public health action to reduce morbidity and mortality and to improve health." A similar definition is used by the World Health Organization (WHO): "Public health surveillance is the continuous, systematic collection, analysis and interpretation of health-related data needed for the planning, implementation, and evaluation of public health practice" (http://www.who.int/topics/public_health_surveillance/en/).

While the purpose of surveillance is often thought of as early warning, and it will be used primarily in this sense in this review, surveillance has many other uses, including evaluating the effectiveness of preventive measures or interventions and providing data for setting disease control priorities. The United States government's recently released *National Strategy for Biosurveillance* ([11]) reinforces the importance of biosurveillance as an essential tool to inform decision makers and maintain a global health perspective.

Perhaps surprisingly, there is no comprehensive list of surveillance systems around the world. However, many of the existing surveillance systems have been well described in several reviews, which are recommended for more detailed information ([9], [12], [13]).

Most surveillance systems are disease specific. International public health surveillance systems include those for influenza, polio, HIV, food-borne diseases, and a number of others. Traditionally, surveillance systems are often classified as "active" and "passive." Most systems are passive, requiring a clinician to notice a possible disease of interest (usually based primarily on a list of notifiable diseases) or unusual clinical presentation and to report cases to appropriate authorities and provide access to the patients and suitable specimens. By contrast, in active surveillance systems the interested agencies (such as health departments) make intensive outreach efforts to find cases. Active surveillance is especially resource and labor intensive, and therefore less common.

The majority of current surveillance systems are also hierarchical and relatively simple in structure: ideally, a clinician (the proverbial "astute clinician") notices a sick individual or animal (more often, a sufficiently large cluster to be noticed) and reports the finding to local health authorities. If deemed warranted, the health authorities (ideally) then conduct epidemiological investigation to identify the source, means of transmission, and additional cases, while following up with laboratory investigation. For human diseases, the responsible governmental body will be the public health agency or (nationally) the ministry of health; for most animal diseases, the cognizant agency will be the agriculture ministry. Wildlife diseases often fall between the cracks. In some countries, if there is a responsible agency, it may be the agriculture ministry, while in other countries it could be the environment ministry. Some countries do have specialized agencies for wildlife. Uganda, for example, has a Wildlife Authority, and Malaysia a Department of Wildlife and National Parks.

The influenza network is a good illustration of a classical surveillance system and is one of the most elaborate. The WHO Global Influenza Surveillance and Response System (GISRS) (known as the Global Influenza Surveillance Network, or GISN, until 2011) is a laboratory-based network established in 1952; it currently has 138 National Influenza Centers in 107 member states, 6 WHO Collaborating Centers, and other components (http://www.who.int/gho/epidemic_diseases/influenza/virological_surveillance/en/). National Influenza Centers are hospital or public health laboratories that are likely to receive specimens from suspected cases of influenza and can identify and subtype influenza (viral surveillance), while the Collaborating Centers are reference or research laboratories. Many illnesses other than influenza can cause influenza-like illness, so laboratory confirmation is essential for accurate diagnosis. As with almost all surveillance systems, because many affected individuals are not sick enough to warrant seeing a clinician, many cases are likely to be missed; others may be overrepresented in areas where there is very intensive surveillance (in epidemiological parlance, ascertainment bias). More recently, recognizing the threat potential of H5N1 avian influenza for human disease (although so far most often occupational), the network has added laboratories for H5N1 and other animal influenzas, an unusual feature for most human disease surveillance systems (but a welcome addition).

This structure is generally mirrored at the national level, although some of the components may differ depending on national capacity and priorities, and may be much more limited in many countries (especially in the developing world). In the United States, there are five nationally dispersed components coordinated by the CDC (http://www.cdc.gov/flu/weekly/overview.htm): viral surveillance by a laboratory network (a number of which feed into the WHO system through the CDC); outpatient surveillance for influenza-like illness by volunteer health care providers (a network of "sentinel physicians"); weekly reports of pneumonia and influenza deaths, in both adults and children, from vital statistics offices in 122 U.S. cities; in selected locations, intensified hospital surveillance for laboratory-confirmed influenza-related hospitalizations in children and adults; and weekly reports from state health departments on estimated level of spread of influenza activity in their state. Some of these components are also part of a state system, and the state forwards the data to the CDC.

Even for influenza, however, there are many gaps in the global system, both geographically and for surveillance of such important animal hosts as pigs, poultry, and waterfowl, as was demonstrated by the last influenza pandemic in 2009—the virus is now known officially as influenza A(H1N1)pdm09—which apparently originated in pigs in Mexico (14, 15).

INTERNATIONAL REPORTING SYSTEMS

Surveillance for many common diseases is fairly routine, and the reports are often just tabulated and filed. However, some have the potential to spread internationally or are of special global concern. As a function of its national sovereignty, each country can decide whether and when to report such an outbreak. In the past, criteria for international reporting were ad hoc, based on the judgment of national governments. The delays in initial reporting of early cases of SARS in China are indicative of the shortcomings of this approach (16, 17). In recent years, there have been increasing efforts to encourage governments to report more systematically and rapidly. For human public health surveillance, the revised, legally binding WHO International Health Regulations, known as IHR(2005), were adopted by the World Health Assembly (the governing body of the WHO) in May 2005 and went into effect in 2007. The revised IHR represent an important paradigm shift (18). They replace the old list of three specific diseases (cholera, yellow fever, and plague) with a broader, syndrome-oriented approach that encourages surveillance for both known and previously unknown infectious diseases. The concept of a public health emergency of international concern, requiring reporting to the WHO within 24 hours of assessment, is introduced and defined. For the first time, a decision tree has been developed to specify criteria for assessing a potential public health emergency of international concern. This may be an unusual disease event based on the clinical presentation; a known disease of concern such as polio, yellow fever, or pneumonic plague; or a novel influenza strain or new antibiotic-resistant pathogen. In another important innovation, the revised regulations specify national core capacity requirements for surveillance and response. Although there is a need for further development of decision criteria and triggers for response, these innovations are a major advance that will require each nation to have a real-time event-monitoring system and strengthened surveillance capabilities.

For animal health, the criteria for surveillance and response are delineated in the Terrestrial Animal Health Code of the World Organisation for Animal Health (Office International des Épizooties, or OIE) (19) and are roughly analogous to those in the IHR (the criteria have actually been in effect longer than the revised IHR). International reports to the OIE are usually submitted by the chief veterinary officer of the reporting country on behalf of the government. Some diseases (currently called listed diseases) are considered to be of particular concern, and countries are expected to notify the OIE of outbreaks within 24 hours; the list currently comprises 116 diseases of various species, mostly of livestock but also some diseases of bees, fish, mollusks and crustaceans, and amphibians (http://www.oie.int/en/animal-health-in-the-world/oie-listed-diseases-2012/). The list includes both infectious diseases of concern for agriculture (e.g., foot-and-mouth disease, bluetongue, and African swine fever) as well as zoonotic diseases such as anthrax, brucellosis, bovine spongiform encephalopathy, Nipah, rabies, and Japanese encephalitis, among others. The OIE maintains a publicly available database and Web interface, the World Animal Health Information Database (WAHID) (http://www.oie.int/wahis_2/public/wahid.php/Wahidhome/Home), which also has a secure portal for reporting from national veterinary authorities.

Within the United Nations system, the agency analogous to the WHO in human health is the Food and Agriculture Organization (FAO), whose mission is food security and animal health. The FAO also maintains a global database of animal disease reports, EMPRES

Global Animal Disease Information System (EMPRES-i) (http://empres-i.fao.org/eipws3g/#h=0).

FIRST STEPS TOWARD GLOBAL NETWORKS

In an attempt to alleviate what many saw as the fragmentation of disease surveillance capabilities and the lack of global capacity, in 1993 ProMED (the Program for Monitoring Emerging Diseases) was formed by a group of scientists under the auspices of the Federation of American Scientists. ProMED was intended as an international follow-up to earlier meetings, especially a 1989 National Institutes of Health meeting on emerging viruses [20] and the 1992 Institute of Medicine report [5]. At a series of meetings in Geneva and elsewhere, the ProMED Steering Committee, consisting of some 60 prominent scientists and public health experts from around the world, recommended forming a network of regional centers to identify and respond to unusual disease outbreaks [21]. This could be seen as also elaborating on the system D. A. Henderson originally proposed at the 1989 National Institutes of Health meeting on emerging viruses [6].

The original ProMED concept of the 1990s was for a surveillance network that could both provide early warning of emerging (previously unknown or unanticipated) infections as well as be able to identify the most common infections. The strategy developed was vigilance for unusual clinical presentations of special concern based on particular case definitions (such as encephalitis, or acute respiratory distress with fever in adults); a set of minimum microbiology capabilities at each site, to identify common diseases; and a system to refer unidentifiable samples to successively more sophisticated reference laboratories, through the network, for possible identification (or recognition as a previously unknown pathogen) [21]. The plan also included epidemiological capacity, which could be provided rapidly through the network if needed. While the original ProMED network and plan were largely oriented toward outbreaks of human disease, it was recognized that many of these emerging diseases might be zoonotic, and the Steering Committee and working groups included experts in animal and plant diseases as well as human public health and clinical microbiology.

A few words seem warranted on the origin of ProMED-mail, the Internet service that began as a spinoff from the original ProMED and has taken on a vigorous independent life of its own [50]. Its origin was serendipitous. To provide the globally dispersed ProMED Steering Committee members a consistent means to communicate with one another, in 1994 we connected all members by e-mail. The e-mail system, originally envisioned as a direct scientist-to-scientist network, rapidly developed into a prototype outbreak reporting and discussion list. The decision was made almost immediately to make it publicly available to all at no charge (it remains nonprofit and noncommercial). ProMED-mail is One Health by design, covering reports of human, animal (including wildlife), and plant diseases, including disease crossover events. Fortuitously, its inception preceded by a few years the explosive growth of the Internet, which further extended its reach. Ironically, since then, although significant strides have been made toward the original goal of a network of periurban centers with clinical, epidemiological, and diagnostic capacity for surveillance, there is still no fully functional global network of regional centers of the sort envisioned by D. A. Henderson [6] or the original ProMED plan [21].

However, in recent years there have been promising advances in developing networks to build more complete surveillance capacity. Several of these networks are discussed below and in the following sections, including the WHO's Global Outbreak Alert and Response Network (GOARN); Global Early Warning System for Major Animal Diseases, Including Zoonoses (GLEWS), a joint network developed by the FAO, OIE, and WHO; the CDC's Global Disease Detection (GDD) network; the U.S. Department of Defense's Global Emerging Infections Surveillance and Response System (GEIS); regional or subregional networks, such as the Mekong Basin Disease Surveillance (MBDS) system; and the U.S. Agency for International Development's (USAID) Emerging Pandemic Threats (EPT) program and its surveillance component, PREDICT.

Coordinating data from different surveillance systems has always been challenging (in fact, attempting to overcome this fragmentation was one of the original reasons for forming ProMED). As most conventional surveillance systems are disease specific (for a disease or category of diseases), many valuable reports might be discarded simply because they are outside the scope of the system, even though they may be of intense interest to someone else (here, there is no substitute for a well-trained and alert human brain). Countries may also have political concerns about reporting, as with SARS in China in late 2002. The WHO responded to some of these limitations by developing GOARN (now part of WHO Global Alert and Response, or GAR) in 2000 (http://www.who.int/csr/outbreaknetwork/en/). Initially, GOARN was designed as a "network of networks" for human disease surveillance, with a wide variety of inputs from official surveillance

systems; other formal surveillance networks (such as the WHO regional and country offices, and military and subregional systems like those to be discussed below); and unofficial systems, including nongovernmental organizations and electronic systems like ProMED-mail and the Global Public Health Intelligence Network (GPHIN), developed by the Canadian government in 1998 to search for relevant news reports on the Web. The initial GOARN meeting summary (22) is a useful source of information on the development of the WHO strategy, and also includes interesting snapshots of several surveillance systems not discussed in this review. In the last few years, GOARN has expanded the network to include outbreak response, using e-mail and other mechanisms to inform partners of emergencies and to request technical or field assistance.

CATALYZING ONE HEALTH: H5N1 AND THE TRIPARTITE

H5N1 highly pathogenic avian influenza, which appeared catastrophically in Asia in late 2003, had a galvanizing effect on the implementation of One Health. The effect was reinforced by the experience with SARS earlier that year, and probably by Nipah on farms several years previously, but H5N1 propelled implementation of the One Health approach to the fore. Although human infections with H5N1 were not frequent and were often occupational, they were associated with severe disease and high case-fatality ratios. It became clear that the disease could only be understood and controlled by following the entire transmission chain, from the migratory waterfowl that carried it to the poultry farms and from poultry to human workers and consumers: a One Health approach.

One outcome of these experiences was the accelerated development of GLEWS, a combined surveillance system by the FAO, OIE, and WHO initiated in 2006 (23; additional information available at: http://www.glews.net/). In addition to combining surveillance information, GLEWS has been developing response criteria based on the IHR(2005) and the OIE Terrestrial Animal Health Code and conducting pilot projects on risk assessment. One of the project's stated goals is monitoring of wildlife disease to support One Health.

The United Nations System Influenza Coordination (UNSIC) has strongly advocated the One Health approach, and the USAID funded an avian influenza program with a number of demonstration projects emphasizing biosecurity at the production level to prevent occupational infections, reduction of high-risk behaviors, market incentives for safer poultry, community-level surveillance for sick poultry, and tracking of H5N1 and other influenza viruses in migratory fowl. Experience with H5N1 as a zoonotic infection crossing species barriers also led USAID to recognize that the origins of most emerging infectious diseases are similar to H5N1, and that this concept could be extended. This led USAID to develop its EPT program, discussed below.

The impact of H5N1 led to a series of ministerial meetings, and at the 2010 International Ministerial Conference on Animal and Pandemic Influenza in Hanoi, Vietnam, representatives of some 70 countries approved a concept note jointly presented by the WHO, FAO, and OIE to work together on H5N1 (the Hanoi Declaration) (24). This triad of the FAO, OIE, and WHO is often referred to as the "tripartite." The tripartite agreement was a great step forward in officially committing these three key intergovernmental organizations to develop joint systems and combine their efforts. Although these are relatively new efforts, the agreement sets an encouraging precedent for cooperation among these agencies in support of better-coordinated infectious disease surveillance and in appreciating the value of One Health.

SURVEILLANCE NETWORKS: FROM GLOBAL TO REGIONAL

The CDC has a long history of international activities, both ad hoc and with established research or surveillance sites in a number of countries. Following the SARS outbreak, Congress provided funds to strengthen the CDC's global capacity to rapidly identify and contain disease outbreaks. The major new initiative developed by the CDC for this purpose was the GDD program, under the Center for Global Health, Division of Global Disease Detection and Emergency Response. GDD began in 2004 with Regional Centers in Kenya and Thailand, and now encompasses 10 GDD Centers, with an ultimate goal of 18 centers. In addition to Thailand and Kenya, there are currently GDD Centers in Bangladesh, China, Egypt, the Republic of Georgia, Guatemala, Kazakhstan, India, and South Africa. The centers, overseen by CDC headquarters in Atlanta, GA, are intended to serve as regional platforms, or hubs, for coordinating CDC and partner activities. Programs at each center include a Field Epidemiology and Laboratory Training Program, an International Emerging Infections Program (health care-based surveillance), projects to strengthen laboratory capacity, pandemic influenza surveillance, and in some of the centers, zoonotic investigation and control and risk communication.

In addition to serving as the CDC's primary global platform for surveillance, research, and capacity building, GDD was designated by the WHO to help member states acquire the IHR(2005) core capacities in surveillance and response (http://www.cdc.gov/globalhealth/gdder/gdd/).

An analogous network in the U.S. Department of Defense is GEIS. The Department of Defense has for many years maintained overseas laboratories and surveillance capabilities. This was consolidated several years ago into GEIS, now a division of the Armed Forces Health Surveillance Center (AFHSC) in Silver Spring, MD. AFHSC was formed, in the words of its mission statement, to be the central epidemiological resource and a global health surveillance proponent for the U.S. Armed Forces. The best-known GEIS surveillance centers are the well-established Department of Defense overseas laboratories, currently in Kenya (United States Army Medical Research Unit-Kenya), Egypt (Naval Medical Research Unit 3), Europe, Thailand (Armed Forces Research Institute of Medical Sciences, or AFRIMS), and Peru (Naval Medical Research Unit 6), as well as a number of similar facilities and military medical units in the United States and Asia (25). Most of the centers work regionally, are cooperative efforts between the United States and host country military or research institutes, and often have special research emphasis on regionally important diseases, as well as surveillance for both local and cosmopolitan diseases (such as influenza) and emerging infections. AFRIMS in Bangkok, Thailand, for example, also conducts work in Nepal and has been a center for dengue surveillance and vaccine research, among other projects.

In addition, there are a number of parallel networks in some developing countries sponsored by other governments or organizations, including the Institut Pasteur International Network, with 32 institutes worldwide (http://www.pasteur-international.org/ip/easysite/pasteur-international-en/institut-pasteur-international-network/the-network) and the Rodolphe Mérieux Laboratories of the Mérieux Foundation, begun in 2007 (http://www.fondation-merieux.org/rodolphe-merieux-laboratories-strengthening-health-structures).

A very interesting innovation has been the development of regional disease surveillance networks that have assembled voluntarily, many including both human and animal disease (and in some cases wildlife). The history of these initiatives reflects the changing nature of global health governance. While cooperative public health programs might once have been exclusively bilateral arrangements between governments (and this is still true of many government programs, including GDD and GEIS), newer initiatives increasingly are voluntary multilateral efforts by neighboring countries, often involving public-private partnerships. Several recent reviews discuss the regional networks in detail (26–28). Brief descriptions of these regional networks and others (such as OHASA, the One Health Alliance of South Asia, initiated by EcoHealth Alliance in 2009) are also on the One Health Commission website (http://www.onehealthcommission.org/en/resources/).

These regional or subregional networks include the MBDS, which includes six countries in Southeast Asia (Cambodia, China, Lao PDR, Myanmar/Burma, Thailand, and Vietnam) (27, 29); the Middle East Consortium on Infectious Disease Surveillance (MECIDS), with Israel, Jordan, and the Palestinian Authority; the East Africa Integrated Disease Surveillance Network (EAIDSNet); and the Southern African Centre for Infectious Disease Surveillance (SACIDS). SACIDS includes institutions in Tanzania, Democratic Republic of the Congo, Mozambique, Zambia, and South Africa, as well as other partnerships outside the region, and is explicitly organized on a One Health framework (30).

MBDS, the first, began informally in 1999 at a regional meeting at which health ministers of the six countries agreed to share information and provide mutual assistance on infectious disease events. After a few years of this informal arrangement, the ministers agreed to sign a memorandum of understanding, which was renewed, with expanded goals, in 2007. Commitment occurred at the working and ministerial levels, where common needs and goals were recognized, and was never formalized at the highest levels of government. Another essential element was funding. For MBDS, funding came initially from the Rockefeller Foundation, joined by other funders such as the Nuclear Threat Initiative and its Global Health and Security Initiative, and the Gates Foundation, underscoring the increasingly important role of nongovernmental players. With infectious disease surveillance, one country's success in controlling an infectious disease protects both that country and others (and, conversely, a country's inability to do it endangers its vulnerable neighbors), so the goal of reducing transboundary infectious disease movement was recognized by all the participants as being in their self-interest and served as a strong starting point.

It is too soon to judge the effectiveness and longevity of the regional networks, but the initiative seems promising. Although some have been more successful than others, all have made significant progress. Of the

three initiatives, MBDS is the longest running and arguably the most successful, while MECIDS has had some successes and shows promise in a region with little history of trust, and EAIDSNet has yet to reach its potential ([28](#)).

All the apparently successful efforts share common features. They began informally, but with ministerial buy-in, and started relatively small, with a pilot project or single goal. MECIDS, for example, started with investigating food-borne disease outbreaks. As the participants began to build trust and learned to work together, the network expanded to take on additional tasks. Long ([28](#)) identifies the necessary minimum as "shared interest in a transnational public good," "membership that includes all and only relevant actors," and "creation of a new group identity and building trust through personal, protracted, positive contact," as well as "congruence with international norms and activities of IGOs [intergovernmental organizations]," strengthening core capacities of the members, and "committed founding donors or multiple revenue streams." The WHO's revised IHR have made a fundamental contribution to strengthening the norms, by requiring the 194 signatory countries (the entire membership of the WHO) to report "public health events of international concern," including unusual disease outbreaks. In the long term, sustainability is essential and depends on continuity of efforts and personnel to build trust and human capital. For all these networks, stable funding is no less critical ([27](#), [28](#)).

The Connecting Organizations for Regional Disease Surveillance (CORDS) initiative was developed in 2009 to help tie together the regional networks and encourage networks to share best practices, and is an interesting model for scaling up globally (http://www.nti.org/about/projects/CORDS/).

DETECTING EMERGING INFECTIOUS DISEASES

Despite improvements in recent years, most existing surveillance systems are still unable to identify emerging infectious diseases, which by definition are unexpected and usually previously unknown ([1](#), [3](#)). Although numerous expert groups have long advocated global surveillance ([5](#), [21](#), [31](#), [32](#)), there has not been any global program to develop a framework for surveillance of emerging infections before they reach the human population. This would require a One Health framework, following pathogens across species and across the animal-human interfaces. Part of the reason may well be the relative lack of attention to wildlife until very recently ([2](#), [32](#)).

In 2009, USAID rose to this challenge by initiating its EPT program, which includes PREDICT as the surveillance component. EPT builds on USAID's earlier programs in avian influenza, which increased the agency's awareness of the importance of the One Health approach. In fact, one of the EPT program's stated objectives is "institutionalizing One Health."

The general goal of PREDICT, in its own words, is "to build an early warning system for emerging diseases that move between wildlife and people" in order to preempt pandemics at their source. Many of the risk factors, or drivers, of infectious disease emergence increase pathogen transfer across interfaces between humans and other animals (or between animal species) ([1](#)–[3](#)). Human activities that can facilitate this process often involve changes in land use or population patterns. These include, among others, farming, hunting, live-animal markets, and urbanization. Because many of the most severe zoonotic diseases cause little or no apparent disease in their natural hosts, it is often necessary to test apparently healthy animals, but random testing is likely to have a low success rate. To target the most promising locations for wildlife testing, PREDICT uses risk modeling to identify high-risk sites and interfaces where cross-species transmission appears most likely to occur, and concentrates on host taxa that have historically most often been associated with zoonotic transfers (especially bats, rodents, nonhuman primates, and some birds).

Activities are ongoing in almost two dozen developing countries. An essential part is capacity building, to enable countries to enhance their own surveillance and diagnostic capabilities. Conducted in partnership with national and local governments and in-country scientists and other local personnel, the project brings together workers in a number of disciplines, including field biologists, wildlife veterinarians, epidemiologists, ecological modelers, and laboratory scientists. Activities include field observation and sample collection, reporting, and both broad viral testing (pathogen discovery, discussed further below) and conventional laboratory microbiology. To date, the project has identified over 200 novel viruses spanning a number of viral families, most from bats, rodents, and nonhuman primates.

A digital data system is being used for storing and correlating the data obtained from these diverse sources, which will subsequently be made publicly available on HealthMap (http://www.healthmap.org/predict/). More

information on PREDICT can be found at its website (http://www.vetmed.ucdavis.edu/ohi/predict/index.cfm).

SYNDROMIC SURVEILLANCE: ANOTHER PATH TO ONE HEALTH NETWORKS?

With the advent of widespread and relatively inexpensive computing power, many of the distinctions between databases and surveillance systems have blurred. While some surveillance systems are still paper based, and reports often originate and are maintained as paper-based documents, surveillance information is now increasingly reported, collected, and aggregated electronically into computerized databases, especially at the international level, or at least stored electronically. Databases like the OIE's WAHID are an example. Much more is also being done through Web-based or electronic data collection systems.

This convergence of informatics and public health surveillance is clearly illustrated by the development of "syndromic surveillance" as a complement to conventional surveillance. This approach has garnered increasing interest, especially since 2001. Although there are many definitions of syndromic surveillance, most highlight the use of "nondiagnostic" data—that is, information on possible health events before, or without, definitive laboratory identification of the pathogen—using electronic networks.

Unfortunately, there is some confusion about the terminology, as the term had already been used to refer to surveillance based on clinical presentation. Clinical case definitions have long been used in surveillance (33), particularly for newly recognized diseases before laboratory tests have been developed (e.g., Ebola in 1976 or SARS in early 2003), and they are used to some extent in the revised IHR. This strategy has been used successfully in the smallpox and polio eradication programs and proposed for surveillance of emerging infections in the original ProMED plan (21). This strategy using clinical presentation is now often called "symptomatic" or "case-based" surveillance to distinguish it from the newer meaning of syndromic surveillance.

As the term is currently used, syndromic surveillance includes a wide variety of data sources, including nontraditional ones. Although there is some general agreement about the data sources and methods that fall under the rubric of syndromic surveillance, clear definitions are lacking (34). One widely cited definition comes from the CDC's document for evaluating public health surveillance systems for early detection of outbreaks: "Syndromic surveillance for early outbreak detection is an investigational approach where health department staff, assisted by automated data acquisition and generation of statistical signals, monitor disease indicators continually (real-time) or at least daily (near real-time) to detect outbreaks of diseases earlier and more completely than might otherwise be possible with traditional public health methods (e.g., by reportable disease surveillance and telephone consultation). The distinguishing characteristic of syndromic surveillance is the use of indicator data types" (35). One advantage of syndromic surveillance is the flexibility to add new data sources or locations fairly easily. Veterinary reports and animal disease outbreak information, and even environmental data if desired, can be included to begin building a One Health system.

Many localities and agencies have piloted syndromic surveillance systems, with a variety of data sources, including hospital emergency department data, sales of prescription or over-the-counter pharmaceuticals, employee absenteeism, hospital admissions, medical billing or laboratory records, and many others, limited only by ingenuity and data availability (36–38). The Electronic Surveillance System for the Early Notification of Community-Based Epidemics (ESSENCE II) in the Washington, DC, metropolitan area, and several other networks, include veterinary reports in addition to traditional indicators (39).

Syndromic surveillance understandably has a number of skeptics, who accurately note, among other valid criticisms, that between 2001 and 2012 this approach had not provided advance warning of an outbreak (40). While syndromic surveillance provides opportunities to build larger and more inclusive networks, it is still largely experimental. There is a need to identify the most useful data sources and understand how best to analyze and interpret the results. However, it can be a useful complement to existing surveillance systems and shows great promise for the future.

CONCLUDING REMARKS

Despite the fact that global surveillance has been a primary recommendation of every expert group (5, 6, 21, 31, 32), many gaps remain (41, 42). Capabilities remain fragmented at every level. The very uneven geographic distribution of surveillance capacity in the world is also a major cause for concern. While these reporting mechanisms, and the databases that now support them, are enormous improvements over the capabilities of 2 decades ago, systems remain parallel and largely unconnected. Information sharing (in the jargon of the

field, data fusion and interoperability) is still often severely limited or nonexistent. The description of the numerous—and mostly independent—surveillance networks above is symptomatic of the current degree of fragmentation. The "network of networks" approach, combining data from a variety of sources, is one feasible solution, although this can present challenges for analysis and interpretation. At the very least, all these networks should have the capability to share information seamlessly and "talk" to each other. Many official networks are also reluctant to share information beyond a relatively small circle.

The importance of zoonotic diseases clearly indicates that effective surveillance requires a One Health approach if we wish to preempt future epidemics upstream, before they reach humans (32). Animal surveillance and disease control systems were originally developed for economic and trade reasons, to prevent the spread of agriculturally important diseases, and only secondarily for zoonotic disease or emerging infections surveillance, and therefore need to be expanded to address these threats (43). Even worse, as mentioned above, surveillance of wildlife, an important source of infectious diseases in humans and other animal species (2, 32), is far less systematic, although the OIE has been developing some welcome efforts in wildlife surveillance, which had largely fallen between the cracks before. Clearly, these are areas in need of the type of cross integration that the One Health concept provides.

There are some promising signs. More is being done now than ever before to consider how to develop effective combined and more comprehensive systems, including wildlife. USAID's vision is forward looking and innovative. Systems covering broad or previously underrepresented geographic areas are beginning to fill in some of the dark areas on the map. Networks that combine data from many different sources or target species, such as GOARN and GLEWS, should be able to take advantage of the recent revolutionary advances in informatics and computer technology to identify the common threads in the data reports. GLEWS and the other tripartite efforts show salutary evidence of interagency cooperation and of broader thinking, more realistically based on how infections emerge and spread.

This integration is being replicated on the ground, although only recently begun. When an Ebola outbreak occurred in Kibaale, in western Uganda, in late July 2012, Uganda formed a national task force that included a wide variety of partners, including senior leaders from the ministries of health and agriculture, the Uganda Wildlife Authority, appropriate laboratories, and other partners such as academic centers in Uganda, the CDC, the WHO, Médecins Sans Frontières/Doctors Without Borders, International Federation of Red Cross and Red Crescent Societies, EPT/PREDICT, and others, in functional working groups with specific objectives for each group. Uganda had used a similar approach during a hemorrhagic fever outbreak in 2010 (now attributed to yellow fever). Other countries are also beginning to use the national task force approach to constructively engage the necessary broad range of expertise and improve regular team communication.

The technologies of diagnostics and communications, both of which are essential for surveillance, have made revolutionary advances in the last 2 decades. Perhaps most notably, now mobile phones can send and receive data almost anywhere in the world, enabling more extensive networks with minimal infrastructure needs, and encouraging what has been dubbed "participatory epidemiology" (44). These technological leaps have led to increasing appreciation of (and increased ability to utilize) the power of networks. This is very timely: it will take all our networking power and technological abilities if we hope to have even a chance to outrun the microbes, which could spread at the speed of an airplane.

Laboratory capacity remains in critically short supply, but here too there is some basis for hope. Diagnostic tools that were unimaginable a decade or two ago, such as PCR-based assays and methods for molecular identification of unknown pathogens by conserved sequences, have now become feasible, even for the better research or diagnostic laboratories in developing countries. The latter (finding and identifying previously unknown and unidentifiable pathogens in nature) is now often referred to as "pathogen discovery" (45, 46). In more advanced laboratories, genome sequencing of pathogens and metagenomics (identifying putative pathogen nucleic acid sequences in crude extracts from biological or environmental samples) has begun to enrich pathogen discovery. In one recent study, as an example of the possible shape of things to come, whole-genome DNA sequencing was used to trace an antibiotic-resistant *Klebsiella pneumoniae* infection in a hospital, in the process yielding some surprising results that will inform future epidemiological investigations (47).

Of course, these capabilities are not yet widely available. But if history is a guide, there is potential for great improvement in the foreseeable future. Field laboratory stations are doing assays that were impossible 2 decades ago except in the most advanced facilities. In the future, one hopes that there will be more point-of-care diagnostics at the local or district level, perhaps

reported through mobile telephones in more remote areas. These are hopeful signs for the technical and reporting arenas, as more capability is being developed at increasingly local levels.

But political will and sustained funding are also the lifeblood of global surveillance. There is also, at this moment, some recognition of the urgency of accomplishing these objectives, with some degree of political will, but history has shown this to be too often fleeting. Human capital is essential, but developing it takes time, resources, and stability. Sustainability of capacity, funding, and political will between crises remains a major challenge in the face of the repeated tendency to become complacent until the next crisis galvanizes action once more. Remedying this challenge calls for better advocacy and a clear demonstration of value in economic and development terms, as well as in lives saved or crises averted. With several recent crises and near misses, effective surveillance networks are a wise and critical investment in preventing future disasters.

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REFERENCES

1. **Morse SS.** 1990. Regulating viral traffic. *Issues Sci Technol* **7**:81–84.

2. **Daszak P, Cunningham AA, Hyatt AD.** 2000. Emerging infectious diseases of wildlife—threats to biodiversity and human health. *Science* **287**:443–449.

3. **Morse SS.** 1995. Factors in the emergence of infectious disease. *Emerg Infect Dis* **1**:7–15.

4. **Wolfe ND, Dunavan CP, Diamond J.** 2007. Origins of major human infectious diseases. *Nature* **447**:279–283.

5. **Lederberg J, Shope RE, Oaks SC Jr (ed).** 1992. *Emerging Infections: Microbial Threats to Health in the United States*. National Academies Press, Washington, DC.

6. **Henderson DA.** 1993. Surveillance systems and intergovernmental cooperation, p 283–289. *In* Morse SS (ed), *Emerging Viruses*. Oxford University Press, New York, NY.

7. **Karesh WB, Cook RA.** 2009. One world—one health. *Clin Med* **9**:259–260.

8. **Langmuir AD.** 1963. The surveillance of communicable diseases of national importance. *N Engl J Med* **1268**:182–192.

9. **Thacker SB, Berkelman RL.** 1988. Public heath surveillance in the United States. *Epidemiol Rev* **10**:164–190.

10. **German RR, Lee LM, Horan JM, Milstein RL, Pertowski CA, Waller MN; Guidelines Working Group Centers for Disease Control and Prevention (CDC).** 2001. Updated guidelines for evaluating public health surveillance systems: recommendations from the Guidelines Working Group. *MMWR Recomm Rep* **50**:1–35.

11. **Executive Office of the President, United States Government.** 2012. *National Strategy for Biosurveillance*. http://www.whitehouse.gov/sites/default/files/National_Strategy_for_Biosurveillance_July_2012.pdf (last accessed June 26, 2013).

12. **Hitchcock P, Chamberlain A, Van Wagoner M, Inglesby TV, O'Toole T.** 2007. Challenges to global surveillance and response to infectious disease outbreaks of international importance. *Biosecur Bioterror* **5**:206–227.

13. **Castillo-Salgado C.** 2010. Trends and directions of global public health surveillance. *Epidemiol Rev* **32**:93–109.

14. **Butler D.** 2012. Flu surveillance lacking. *Nature* **483**:520–522.

15. **Peiris JS, Poon LL, Guan Y.** 2012. Surveillance of animal influenza for pandemic preparedness. *Science* **335**:1173–1174.

16. **Zhong NS, Zheng BJ, Li YM, Poon LL, Xie ZH, Chan KH.** 2003. Epidemiology and cause of severe acute respiratory syndrome (SARS) in Guangdong, People's Republic of China, in February, 2003. *Lancet* **362**:1353–1358.

17. **Heymann D, Rodier G.** 2004. Global surveillance, national surveillance, and SARS. *Emerg Infect Dis* **10**:173–175.

18. **World Health Organization.** 2005. *International Health Regulations (2005)*, 2nd ed. World Health Organization, Geneva, Switzerland. http://whqlibdoc.who.int/publications/2008/9789241580410_eng.pdf (last accessed June 26, 2013).

19. **OIE (World Organisation for Animal Health).** 2012. *Terrestrial Animal Health Code (2012)*. OIE, Paris, France. http://www.oie.int/en/international-standard-setting/terrestrial-code/access-online/ (last accessed June 26, 2013).

20. **Morse SS, Schluederberg A.** 1990. Emerging viruses: the evolution of viruses and viral diseases. *J Infect Dis* **162**:1–7.

21. **Morse SS, Rosenberg BH, Woodall J.** 1996. ProMED global monitoring of emerging diseases: design for a demonstration program. *Health Policy* **38**:135–153.

22. **World Health Organization (WHO).** 2000. *Global Outbreak Alert and Response. Report of a WHO Meeting*. WHO, Geneva, Switzerland. WHO/CDS/CSR/2000.3. http://www.who.int/csr/resources/publications/surveillance/whocdscsr2003.pdf (last accessed June 26, 2013).

23. **The FAO-OIE-WHO Collaboration.** 2006. Global Early Warning and Response System for major animal diseases, including zoonoses (GLEWS). www.oie.int/fileadmin/Home/eng/Animal_Health_in_the_World/docs/pdf/GLEWS_Tripartite-Finalversion010206.pdf (last accessed June 26, 2013).

24. **The FAO-OIE-WHO Collaboration.** 2010. Sharing responsibilities and coordinating global activities to address health risks at the animal-human-ecosystems interfaces (A Tripartite Concept Note). http://www.who.int/foodsafety/zoonoses/final_concept_note_Hanoi.pdf (last accessed June 26, 2013).

25. **Russell KL, Rubenstein J, Burke RL, Vest KG, Johns MC, Sanchez JL, Meyer W, Fukuda MM, Blazes DL.** 2011.The Global Emerging Infection Surveillance and Response System (GEIS), a U.S. government tool for improved global biosurveillance: a review of 2009. *BMC Public Health* **11**(Suppl 2):S2. doi:10.1186/1471-2458-11-S2-S2.

26. **Kimball AM, Moore M, French HM, Arima Y, Ungchusak K, Wibulpolprasert S, Taylor T, Touch S, Leventhal A.** 2008. Regional infectious disease surveillance networks and their potential to facilitate the implementation of the International Health Regulations. *Med Clin N Am* **92**:1459–1471.

27. **Moore M, Dausey DJ, Phommasack B, Touch S, Guoping L, Nyein SL, Ungchusak K, Vung ND, Oo MK.** 2012. Sustainability of sub-regional disease surveillance networks. *Global Health Governance* **5**:1–43. http://blogs.shu.edu/ghg/?s=moore.

28. **Long WJ.** 2011. *Pandemics and Peace: Public Health Cooperation in Zones of Conflict*. United States Institute of Peace Press, Washington, DC.

29. **Yong E.** 2011. Disease trackers. *BMJ* **343**:d4117. doi:10.1136/bmj.d4117.

30. Coker R, Rushton J, Mounier-Jack S, Karimuribo E, Lutumba P, Kambarage D, Pfeiffer DU, Stärk K, Rweyemamu M. 2011. Towards a conceptual framework to support one-health research for policy on emerging zoonoses. *Lancet Infect Dis* **11:**326–331.

31. Smolinski MS, Hamburg MA, Lederberg J (ed). 2003. *Microbial Threats to Health: Emergence, Detection, and Response.* National Academies Press, Washington, DC.

32. Keusch GT, Pappaioanou M, Gonzalez MC, Scott KA, Tsai P (ed). 2009. *Sustaining Global Surveillance and Response to Emerging Zoonotic Diseases.* National Academies Press, Washington, DC.

33. Centers for Disease Control and Prevention. 1997. Case definitions for infectious conditions under public health surveillance. *MMWR Recomm Rep* **46:**1–55.

34. Henning KJ. 2004. What is syndromic surveillance? *MMWR Morb Mortal Wkly Rep* **53**(Suppl)**:**7–11.

35. Buehler JW, Hopkins RS, Overhage JM, Sosin DM, Tong V; CDC Working Group. 2004. Framework for evaluating public health surveillance systems for early detection of outbreaks: recommendations from the CDC Working Group. *MMWR Recomm Rep* **53:**1–11.

36. Centers for Disease Control and Prevention (CDC). 2004. Syndromic surveillance. Reports from a national conference, 2003. *MMWR Morb Mortal Wkly Rep* **53**(Suppl)**:**1–264.

37. Mostashari F, Hartman J. 2003. Syndromic surveillance: a local perspective. *J Urban Health* **80**(2 Suppl 1)**:**i1–i7.

38. Das D, Weiss D, Mostashari F, Treadwell T, McQuiston J, Hutwagner L, Karpati A, Bornschlegel K, Seeman M, Turcios R, Terebuh P, Curtis R, Heffernan R, Balter S. 2003. Enhanced drop-in syndromic surveillance in NYC following September 11, 2001. *J Urban Health* **80**(2 Suppl 1)**:**i76–i88.

39. Lombardo J, Burkom H, Elbert E, Magruder S, Lewis SH, Loschen W, Sari J, Sniegoski C, Wojcik R, Pavlin J. 2003. A systems overview of the Electronic Surveillance System for the Early Notification of Community-Based Epidemics (ESSENCE II). *J Urban Health* **80**(2 Suppl 1)**:**i32–i42.

40. Reingold A. 2003. If syndromic surveillance is the answer, what is the question? *Biosecur Bioterror* **1:**77–81.

41. United States Government Accountability Office (GAO). 2001. *Global Health: Challenges in Improving Infectious Disease Surveillance Systems.* Report GAO-01-722. GAO, Washington, DC. http://www.gao.gov/assets/240/232631.pdf (last accessed June 26, 2013).

42. Feng Z, Li W, Varma JK. 2011. Gaps remain in China's ability to detect emerging infectious diseases despite advances since the onset of SARS and avian flu. *Health Aff (Millwood)* **30:**127–135.

43. Kuiken T, Leighton FA, Fouchier RA, LeDuc JW, Peiris JS, Schudel A, Stöhr K, Osterhaus AD. 2005. Pathogen surveillance in animals. *Science* **309:**1680–1681.

44. Freifeld CC, Chunara R, Mekaru SR, Chan EH, Kass-Hout T, Ayala Iacucci A, Brownstein JS. 2010. Participatory epidemiology: use of mobile phones for community-based health reporting. *PLoS Med* **7:**e1000376. doi:10.1371/journal.pmed.1000376.

45. Lipkin WI. 2010. Microbe hunting. *Microbiol Mol Biol Rev* **74:**363–377.

46. Relman DA. 2011. Microbial genomics and infectious diseases. *N Engl J Med* **365:**347–357.

47. Snitkin ES, Zelazny AM, Thomas PJ, Stock F, NISC Comparative Sequencing Program, Henderson DK, Palmore TN, Segre JA. 2012. Tracking a hospital outbreak of carbapenem-resistant *Klebsiella pneumoniae* with whole-genome sequencing. *Sci Transl Med* **4:**148ra116. doi:10.1126/scitranslmed.3004129.

48. Woolhouse MEJ, Adair K, Brierley L. 2013. RNA viruses: a case study of the biology of emerging infectious diseases. *Microbiol Spectrum* **1**(2): OH-0001-2012. doi:10.1128/microbiolspec.OH-0001-2012.

49. Reperant LA, Osterhaus ADME. 2013. The human-animal interface. *Microbiol Spectrum* **1**(1):OH-0013-2012. doi:10.1128/microbiolspec.OH-0013-2012.

50. Madoff LC, Li A. 2013. Web-based surveillance systems for human, animal, and plant diseases. *Microbiol Spectrum* **1**(3):OH-0015-2012. doi:10.1128/microbiolspec.OH-0015-2012.