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Enhancing global health security in Thailand: Strengths and challenges of initiating a One Health approach to avian influenza surveillance

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ABSTRACT

Infectious disease surveillance systems support early warning, promote preparedness, and inform public health response. Pathogens that have human, animal, and environmental reservoirs should be monitored through systems that incorporate a One Health approach. In 2016, Thailand's federal government piloted an avian influenza (AI) surveillance system that integrates stakeholders from human, animal, and environmental sectors, at the central level and in four provinces to monitor influenza A viruses within human, waterfowl, and poultry populations. This research aims to describe and evaluate Thailand's piloted AI surveillance system to inform strategies for strengthening and building surveillance systems relevant to One Health. We assessed this surveillance system using the United States Centers for Disease Control and Prevention's (U.S. CDC) "Guidelines for Evaluating Public Health Surveillance Systems" and added three novel metrics: transparency, interoperability, and security. In-depth key informant interviews were conducted with representatives among six Thai federal agencies and departments, the One Health coordinating unit, a corporate poultry producer, and the Thai Ministry of Public Health-U.S. CDC Collaborating Unit. Thailand's AI surveillance system demonstrated strengths in acceptability, simplicity, representativeness, and flexibility, and exhibited challenges in data quality, stability, security, interoperability, and transparency. System efforts may be strengthened through increasing laboratory integration, improving pathogen detection capabilities, implementing interoperable systems, and incorporating sustainable capacity building mechanisms. This innovative piloted surveillance system provides a strategic framework that can be used to develop, integrate, and bolster One Health surveillance approaches to combat emerging global pathogen threats and enhance global health security.

1. Background

Infectious disease surveillance is a fundamental global health security tool that aids in the detection and containment of diseases locally, nationally, and globally. Robust surveillance systems support efforts to disrupt infectious disease transmission through early warning signals, disease control activities information, and contextual basis for contact tracing investigation [1,2]. Further, successful surveillance systems

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benefit from strong collaborations between the laboratory and epidemiology sectors to ensure effective and rapid sample collection, pathogen identification, and the quantification of disease in a population [3–5]. Beyond the laboratory-epidemiology partnership, multidisciplinary disease surveillance systems are critical to address emerging infectious diseases, which threaten global health security [6].

Approximately 75% of emerging infectious diseases are zoonotic [7]; consequently One Health approaches may be used to predict [8], detect [9], prevent [10], and control [11] zoonoses. However, many emerging infectious disease surveillance activities are fragmented into separate exposure routes (foodborne, respiratory, healthcare associated) or divided by pathogen (e.g., influenza, coronaviruses). Human and animal disease surveillance systems are often separated, as well: human surveillance systems are dedicated to human disease detection, while animal disease surveillance systems focus on animal disease detection [12]. Alternatively, One Health infectious disease surveillance systems rely on human, animal, and environmental health organizations to form communication and information networks or tertiary systems that harmonize all One Health domains [13]. Surveillance systems may leverage independent components and resources; however, agencies could benefit through unification of data, reporting, and response efforts. For example, surveillance activities among livestock and wildlife serve as important sentinels for human disease and may be used to identify, monitor, and respond to early indicators of known and novel biological threats [14,15]. Additionally, the emergence of zoonotic diseases, including influenza subtypes of pandemic potential [10], Ebola [7], Zika [16], and MERS [17,18] have heightened awareness for necessity and utility of One Health [19–21].

Governments and international health organizations [22] have started to adopt One Health surveillance approaches to tackle global health security threats and support pandemic preparedness efforts. Such systems vary in geographic location and size, pathogens of interest, stakeholder coordination, and One Health capabilities. Several public health entities have implemented and maintained multi-sectoral surveillance systems that integrate human and animal disease detection. Among them, summarized by Bordier et al. [13], northern Italy has initiated a One Health surveillance system for West Nile Virus [23], Mongolia for multiple zoonotic pathogens [24], and Taiwan for zoonotic influenza [25].

Other than Taiwan, few other governments have adopted influenza surveillance systems that monitor animal reservoirs side-by-side with human cases [26]. Surveillance systems that monitor influenza, a disease that experts have projected to be a leading zoonotic pathogen to cause future pandemics [27–29], should incorporate a One Health approach due to the pathogen's capacity to infect many animal species, demonstrated spillover, and potential for significant morbidity and mortality [30]. Establishing a robust One Health surveillance system for influenza may be most critical in regions where human spillover has been documented, such as in Southeast Asia [28].

Thailand, a country which reported its first H5N1 avian influenza (AI) human infection in 2004 [31], has exhibited both substantial human [32] and economic losses in the form of trade and tourism due to avian influenza [33,34]. Although Thailand has not reported a human case since 2004, AI poses a constant threat [35,36]. Therefore, Thailand has recognized the necessity to establish a One Health surveillance system to monitor AI in wild birds and poultry and detect disease spillover into the human population [37]. In 2016, stakeholders piloted a One Health approach to AI surveillance in four provinces, which integrates the animal, human, and environmental sectors among government agencies, academia, and the private sector. Thailand's AI surveillance system has neither been studied nor evaluated comprehensively. This research aims to describe its structure, map the network of stakeholders involved, and illustrate the strengths and challenges of the system's activities. Further, this study strives to inform recommendations for future surveillance systems in Thailand and elsewhere to detect and monitor other zoonotic and high consequence diseases to enhance global health security.

2. Methods

2.1. One Health surveillance stakeholder interviews

Thailand's AI One Health surveillance structure and activities were investigated through semi-structured, in-depth key informant interviews with partners who have implemented, participated in, and supported AI surveillance efforts. Key informants were identified by a roundtable discussion with experts from Thailand's Ministry of Public Health (MoPH) to ensure representation from all One Health and technical surveillance entities. The interviewees represented three divisions of the MoPH's Department of Disease Control (DDC), the Public Health Laboratory (PHL) at the National Institute of Health (NIH), the National Institute of Animal Health (NIAH) Laboratory, the Department of Livestock Development (DLD), the Department of National Parks Wildlife and Plant Conservation (DNP), a collaborating private poultry corporation, and the MoPH-U.S. CDC Collaboration (TUC). Within the MoPH DDC, the Division of Epidemiology (DoE), the Office of International Cooperation (OIC), and the Coordinating Unit for One Health (CUOH) were interviewed. One leader involved with the surveillance system from each agency was interviewed.

The semi-structured interview format ensured consistent surveying while also maintaining flexibility to gather unanticipated information and allow for follow-up questions. An interview guide was developed to assess critical surveillance system components and to evaluate the flow of data, communication, and public health response. Key informant interviews were planned for 60–90 min and were held on audio/video web-based software. For consistency, the same interviewer introduced the goals of the project and led the interview; however three researchers were involved in every call to help facilitate, add thoughts, and troubleshoot any technical difficulties. Every interview was recorded for data extraction purposes, and each participant was verbally consented beforehand. After interviews, the interviewer emailed participants follow-up questions if particular subjects necessitated further clarification or to close knowledge gaps. The study was determined to be exempt from human subjects research approval by the Johns Hopkins Bloomberg School of Public Health Institutional Review Board (IRB#12894).

2.2. Surveillance system evaluation metrics

Semi-structured interview questions were developed to collect data on the strengths and challenges of Thailand's piloted AI surveillance system using the United States Centers for Disease Control's (U.S. CDC) updated "Guidelines for Evaluating Public Health Surveillance Systems" (henceforth, "U.S. CDC Evaluation Guidelines") framework [38]. The U.S. CDC Evaluation Guidelines has been used and validated in studies to evaluate surveillance programs across the world, including Brazil [39], Ghana [40], Jordan [41], Yemen [42], and others [43]. The U.S. CDC Evaluation Guidelines considers nine metrics: i) simplicity, ii) flexibility, iii) data quality, iv) acceptability, v) sensitivity, vi) predictive value positivity, vii) representativeness, viii) timeliness, and ix) stability. Three additional metrics developed by the authorship team and used to evaluate the surveillance system: x) transparency, xi) interoperability, and xii) security (Table 1). Surveillance systems evolve in parallel to public health threats and technologies, and these three new metrics facilitate assessing emerging surveillance system components that are critical to digital data collection, storage, and communication [44]. Taken together, these 12 metrics provided a basis from which to evaluate the strengths and challenges of the piloted AI surveillance system in Thailand.

Table 1
Surveillance system evaluation metrics and associated strengths and challenges of Thailand's One Health Avian influenza surveillance system.

Metric	Strengths	Challenges
Simplicity Intuitive structure of surveillance system and ease of operation	• Three government agencies (MoPH, DLD, and DNP) lead system with a coordinating unit (CUOH) acting as a monitoring and engagement hub • Integration exists within data collection, emergency response, and training activities • Informal and formal mechanisms exist to share data (e.g. social media applications, phone calls, and official hardcopy reports) • One Health approach describes events in human and avian populations	• Multiple formal and informal data sources for multiple species enter the system • Lacking an integrated, interoperable data system • Low level of integration of laboratories, non-human resources, and data • Effort and time to manage and disseminate samples and data are high
Representativeness Accuracy of health related events described over time and distribution in population	• Active and passive system components aim to increase the representativeness of human populations (e.g. obtaining data from urban and rural areas; using both private and public hospitals in the sentinel network)	• Environmental sampling of water sources and of high-risk transmission environments are currently not conducted • Swine species are not monitored or surveyed • Only public hospitals conduct sentinel surveillance
Flexibility Adaptability of the system is to modify practices with changes to information and technology	• Adaptable case definitions that have been changed to increase sensitivity and adapt to local situations • Human resource surge capacity plans exist (and tested during COVID-19 pandemic) • Data can enter the surveillance system through multiple formal and informal sources: official report, phone call, mobile phone application reports, sentinel sources, and event-based triggers	• Human and animal laboratory networks encounter resource obstacles in surge situations (e.g. epidemics and pandemics) • Laboratory structure is currently vertically based upon pathogen type and species
Acceptability Willingness to contribute to the surveillance system outside organization/ sponsoring agencies	• Strong acceptability for a One Health approach at the central, national government level • District and Provincial-level governments have been willing to contribute and provide human resources • International organizations are willing to contribute funding and technical assistance such as the U. S. CDC, WHO, and FAO • Private poultry industry has been engaged	• Lack of political will at the local level in other provinces without pre-existing collaborations
Data Quality Completeness and validity of data	• Paper records are digitized in formal spreadsheets • Multiple sources of data for informed situational awareness such as case reports, epidemiologic data, mobile phone reports, and laboratory data	• Lacking integrated database(s) which hinders data sharing • Data from mobile application not automatically ingested into existing database • Potential introduction of errors from paper to digital entry
Sensitivity Ability of a system to detect a health event	• System designed to capture multiple case definitions • Systems aims to differentiate between seasonal, pandemic, and novel influenza viruses	• Gaps in data to systematically measure sensitivity
Timeliness Estimated time between steps and timescale of system	• Established timeliness targets: o <24 h from abnormal event to sample collection o 6 h between sample collection and submission to regional laboratory o <48 h from sample collection and regional laboratory result or referral to central laboratory o Post-laboratory result suspected avian influenza are reported within 24 h	• Gaps in data to systematically measure timeliness • Samples may need to travel long distances to regional and central laboratories delaying reporting • Intensive laboratory assays delay surveillance processes (e.g. sample plating to viral isolation results may take up to 12 working days)
Stability Reliability of operations, especially under system stress	• Hospital human resources are supplemented by public health volunteers at the village/district levels • Situational Awareness Teams (SAT) comprised of multidisciplinary staff are able to deploy to high risk situations • Multiple IT technicians operate and repair the system • Potential expansion to other provinces	• Human resources are limited at the laboratory level • Sample cold chain not always reliable across surveillance network • System lacking surge capacity, highlighted by the COVID-19 pandemic • Relies on external funding cycles
Security Protective mechanisms to prevent data compromise	• Designated servers with access restrictions exist to store some surveillance data sources	• Paper data sources used for some system components • Hardcopy data can be easily compromised • Electronic systems do not have multiple layers of security
Interoperability Ability and ease for information to cross intra- and inter-agency boundaries	• Trainings, meetings, and response teams integrate human and animal health staff • Communications and reports are shared between human and animal health government agencies • Consistent messaging applications used for informal communications	• Surveillance data systems are not yet interoperable between species, geographic units, and pathogens • Multiple applications and programs exist both within agencies (from epidemiology to laboratory to administrative) and between agencies • No consistent formal communication technologies and pathways • Most information dissemination is paper based • Existence of three surveillance-related

(continued on next page)

Table 1 (*continued*)

Metric	Strengths	Challenges
		mobile phone applications that are unable to easily integrate data
Transparency Extent to which information can be and is shared across member agencies	• Data shared during bi/ triannual stakeholder meetings • Data shared immediately between partners when high consequence influenza samples are identified • Public and private sector surveillance partnerships	• Data is not consistently shared in real-time or on a scheduled basis apart from low frequency meetings

3. Results

3.1. Surveillance system stakeholder roles and network

Thailand has adopted a "trans-professional" approach through a partnership with governmental agencies, academic institutions, and the private sector. On the central government level, the surveillance system partnership is comprised of the MoPH (human focused), the DLD (livestock focused), the DNP (wildlife focused), and their respective laboratory entities (Fig. 2). Within NIH, PHL and the regional laboratory network analyze suspected AI samples collected from humans. The NIAH Laboratory analyzes suspected AI samples from animals including domestic and wild birds (livestock and wildlife sectors collaborate and use the same laboratory facilities). Multiple AI surveillance stakeholders work under the MoPH's DDC, the central public health department responsible for infectious disease epidemiology, surveillance, and control, such as the DoE, OIC, and the CUOH. The DoE is responsible for surveillance and epidemiology, and the OIC tackles activities related to cross-border and internal surveillance. Thailand also founded the CUOH, located within the MoPH, which coordinates staff, research,

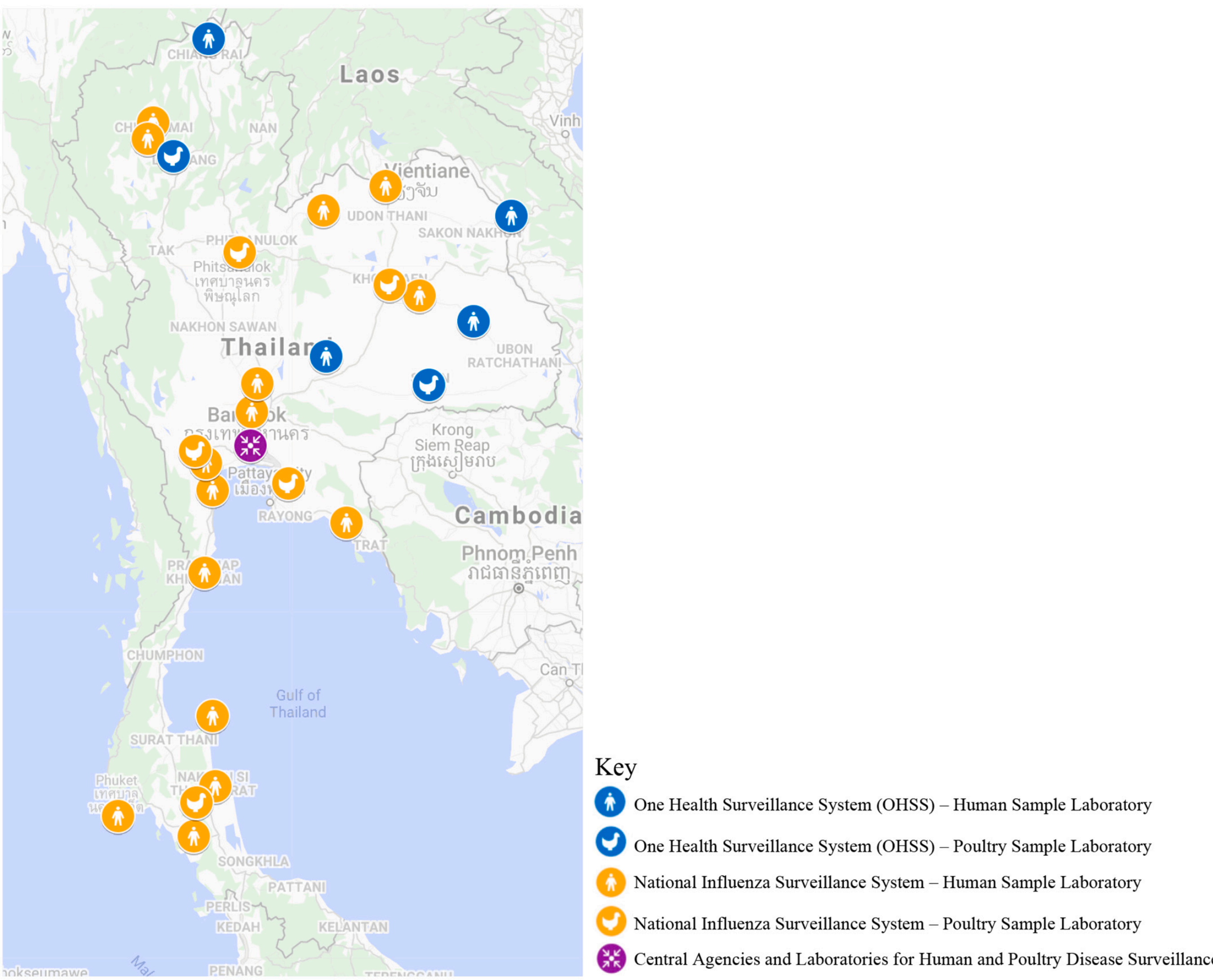

Fig. 1. Map of Thailand's avian and human influenza surveillance system laboratory network. Thailand's avian influenza One Health surveillance system is located in Chiang Rai, Ubon Ratchathani, Nakhon Phanom, and Mukdahan provinces and represented by the blue color. The yellow color represents the national, species-focused surveillance system. Types of species sampled are denoted by the figure within each point. The central laboratories, which test either human and animal specimen are located in Bangkok, denoted by the purple point and the target-like symbol. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

conferences, training, and public health response across One Health-related government agencies. This coordinating-unit maintains an interagency communication channel and facilitates cross-governmental implementation of One Health activities. The TUC coordinates and supports AI surveillance efforts in border provinces. Unlike traditional surveillance systems, Thailand has integrated both academic and private institutions into its surveillance network. These non-governmental entities lead active and passive AI surveillance activities independently and have been engaged by the CUOH to initiate results-sharing and joint training with the One Health surveillance network (Fig. 2 illustrates a network diagram).

3.2. Mapping Thailand's One Health Avian Influenza surveillance system and steps

In 2016, Thailand's MoPH and DLD piloted a One Health AI surveillance system in four provinces: Chiang Rai, Ubon Ratchathani, Nakhon Phanom, and Mukdahan Province (Fig. 1). Provinces were selected based upon their poultry production density, live bird markets, migratory bird flyways, and local government acceptability of the One Health surveillance network. Interagency surveillance stakeholders aimed to integrate AI detection, coordination, and training activities using a One Health approach. Historically, influenza surveillance in humans and animals had been executed separately [45]. However, this One Health-based system aimed to facilitate communication, data collection and transfer, and response pathways by linking human, animal, and environmental health agencies at all levels: central, provincial, and district.

Thailand's AI surveillance system structure can be further divided into five sequential components that monitor, analyze and respond to potential AI threats: 1) surveillance triggering events, 2) sample collection, 3) laboratory analysis, 4) data interpretation and sharing, and 5) communication and response activities (Fig. 2). Each component is a critical step for both surveillance and public health response activities, possessing active and passive components. Active AI surveillance includes the surveillance of poultry at live bird markets and poultry farms each month and the targeted surveillance of wild birds twice per year. Sample collection is performed by district and provincial level DLD staff, who collaborate and communicate regularly with the public health office of the human domain. Resources for active surveillance are also mobilized during suspected human and animal influenza cases. Passive AI surveillance is conducted through telephone alerts, in-person informants, and mobile phone applications that are used to document abnormal events in humans and birds. Three mobile phone applications (apps)—an academic-initiated PODD app [46], the CUOH's app, and a DLD app developed for farmers—are publicly available to report potential influenza-related abnormal events. Abnormal event reports can be initiated by local community members and farmers or individuals operating in the formal surveillance structure such as One Health volunteers, veterinarians, and physicians.

A suspected AI case or abnormal event in humans or animals triggers a cascade of public health actions. First, sample collection is initiated and performed by the district or provincial office, which is dependent upon the species which triggered the event: the public health office for humans and the livestock office for animals. However, the lead entity coordinates with the non-triggered office to maintain open One Health

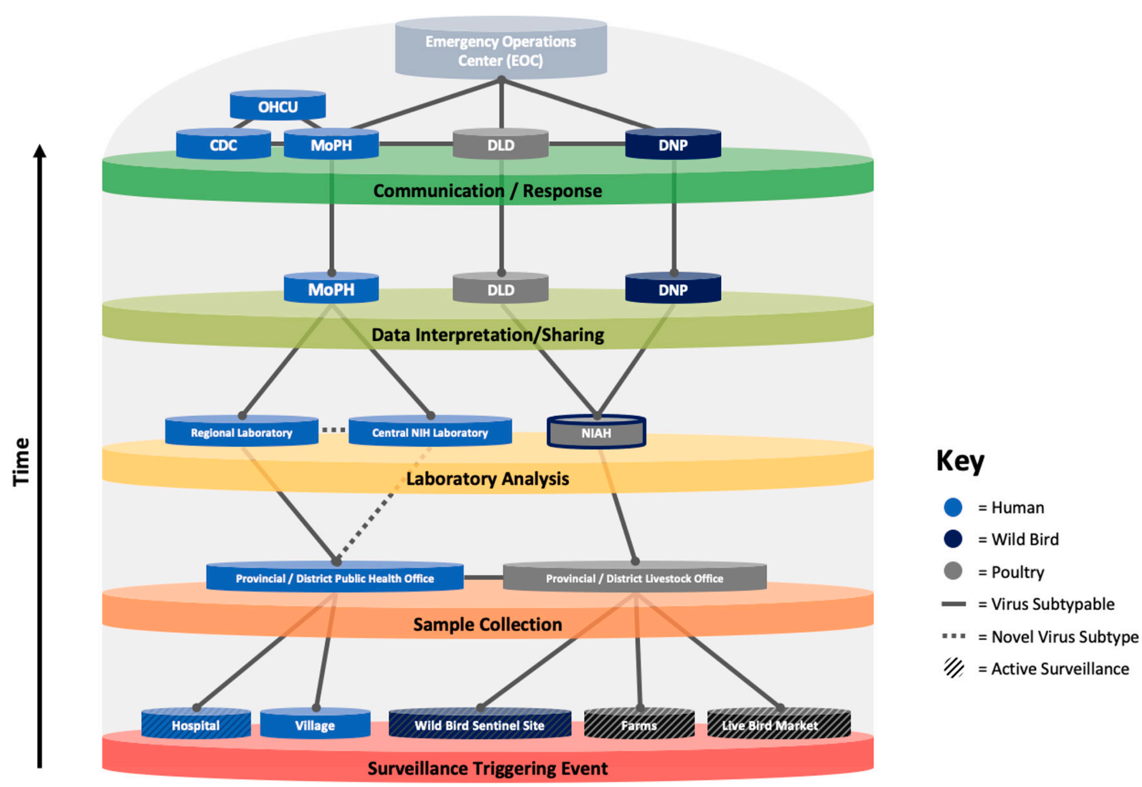

Fig. 2. Thailand's avian influenza One Health surveillance system stakeholder network and surveillance system structure among governmental agencies, which represents Chiang Rai, Ubon Ratchathani, Nakhon Phanom, and Mukdahan provinces. Each stakeholder is denoted by blue or grey labeled cylinders connected by links that indicate information sharing across each of the five sequential surveillance components: triggering events, sample collection, laboratory analysis, data interpretation/sharing, and communication/response. Horizontal links between stakeholders represent One Health collaborations among different species sectors. Governmental entities may be present at several layers, which illustrates their broad role in the One Health Surveillance System. CDC, United States Centers for Disease Control and Prevention; DLD, Division of Livestock Development; DNP, Department of National Parks Wildlife and Plant Conservation; MoPH, Ministry of Public Health; NIH, National Institutes of Health; NIAH, National Institute of Animal Health; OHCU, One Health Coordinating Unit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

communication channels. After collection, the sample is shipped to the regional laboratory network—a subset of laboratories forming a geographically dispersed network to reduce sample travel time and burden on the central laboratory—for RT-PCR confirmatory testing. Samples with either positive or inconclusive results are then shipped to the central laboratory for subsequent analyses.

The human and animal agencies collaborate closely during surveillance alerts to collect samples and ship specimen to the laboratory for further analysis. Although the regional laboratory networks and central laboratories are species-specific and do not share resources or communicate findings, once sample results are reported to the fifth and final level of the system, information is shared with the relevant central agency such as the DOE at the DDC or the Bureau of Disease Control and Veterinary Services at DLD. Then, the DOE and the DLD initiate One Health communication, response, and data sharing efforts.

3.3. Surveillance system strengths

Thailand's AI One Health surveillance system was evaluated with the nine U.S. CDC's Surveillance System Evaluation Guidelines parameters and three additional metrics which we developed to adapt with technological advances. Along with the definition of each metric, Table 1 details surveillance system strengths and challenges. Thailand's One Health surveillance system strengths were its acceptability, simplicity, representativeness, and flexibility. An effective component of the AI surveillance system was its ability to assemble supporters from all governmental levels. For example, a cadre of village health volunteers (VHVs) support Thailand's surveillance system on location. VHVs are comprised of a trusted, self-reliant community member network who monitor and report to their respective jurisdictions for signs of influenza-like illness (human and avian). Surveillance stakeholders span the local, district, provincial, regional, and national level, which demonstrates its *acceptability*. The acceptability metric applies beyond a system's ability to mobilize individuals. Thailand's AI surveillance system, initially developed and founded by the COOH, DLD, DNP, and MoPH, has been promoted throughout the Thai government. Thai stakeholder involvement has expanded beyond the public sector and into the private poultry sector. International organizations have also accepted Thailand's surveillance system evidenced by WHO, FAO, and U.S. CDC, which have all provided technical assistance and funding to support Thailand's efforts.

Beyond its widespread acceptance, Thailand's AI surveillance system framework forms a pyramidal structure, which demonstrates the system's *simplicity*. The base tier comprises local tracking of abnormal events and conduct sample collection, while information and data are sent to the regional laboratory network, central laboratory, and finally to the central disease control unit at its apex. When uncommon and highly consequential strains of influenza are identified, the central disease control unit communicates with the provincial and district levels to initiate response activities. Governmental agencies involved in the One Health surveillance system (i.e. MoPH, DLD, and DNP) collaborate with the Coordinating Unit for One Health (CUOH) to disseminate findings and respond to threats. These government surveillance partners have established both formal and informal lines of communication to increase their working relationship and provide consistency in data collection and interpretation, training, and emergency response mechanisms.

Representativeness is another system strength given that multiple forms of surveillance, species, and stakeholders are integrated for the common global health security goal of survey and control AI. Although the geographic representativeness is a challenge, Thailand plans to expand this pilot to additional provinces based upon feasibility and practicality. Thailand has initiated its AI surveillance system in four provinces (of 77), strategically selected based upon their collectively high proportion of Thailand's total live bird markets and avian border crossings. Combining active surveillance strategies (by directly sampling humans and birds at poultry operations) and passive surveillance strategies (through gathering data from hospital systems), the surveillance system captures events with high sensitivity in both urban and rural settings within the piloted provinces. The active surveillance component occurs four times a year, as opposed to annual surveillance in the human arm. Active seasonal sampling provides information to predict variations in specific influenza infection incidence that may help tailor surveillance and response efforts.

Thailand's pilot surveillance program demonstrated *flexibility* through three primary actions: 1) integration of new technologies, 2) incorporation of diverse data sources, and 3) surge capacity planning. With the advent of developed diagnostic technologies, Thailand's surveillance system has expended surveillance resources to develop those capacities and employ them in the field. Specifically, scientists utilize RT-PCR to detect AI strains of pandemic potential and respond accordingly. The system has also started to implement fieldable, rapid PCR platforms in surveillance activities. Diverse and new data sources are integrated into surveillance such as phone calls from farmers to more advanced event-based mobile phone application reporting. With the acquisition of new data from local and regional sources, the surveillance system modifies resource allocations to balance surveillance mechanisms to be both proactive and reactive to emerging situations. Thailand has protocols for surge capacity in cases of systemic shocks due to abnormally high-incidence epidemic events. These procedures were recently challenged during the COVID-19 pandemic, and Thailand was successful in its capacity expansion to meet the heightened case load.

3.4. Surveillance system challenges

The system exhibited challenges in data quality, interoperability, security, and transparency. Each level of the surveillance system has opportunities to more effectively transition from triggering event recognition to sample collection and finally results dissemination. *Data quality* and efficiency could be optimized at multiple levels of data collection, which is further complicated by multiple data collection systems three mobile apps, email, phone, and verbal warnings without direct data entry into a common database system. The data collected from these widespread reporting mechanisms requires manual entry via paper-based form and transferred to electronic spreadsheets, exposing the process to constraints on human resources, the potential for errors, and possible data quality problems. Viral isolate integrity was also difficult to maintain due to the many steps during collection practices, contamination, travel time from collection point to laboratories, and maintenance of cold chain.

Interoperability is a critical metric for a One Health surveillance system as human, animal, and environmental data must be integrated at a consistent level to inform and execute public health action. The measure of a surveillance system's interoperability can be evaluated by multiple characteristics such as the interoperability of data from different sentinel hospitals collecting influenza data, stakeholders such as the government and private industry, and species such as humans and poultry. Thailand's AI surveillance system faced data interoperability challenges at the local, provincial, and national levels. Technical capabilities to alleviate these challenges related to data interoperability between species have been difficult to build. AI has different human and zoonotic case definitions, investigation triggers, and laboratory protocols. Surveillance stakeholders also cited interoperability challenges related to communication and reporting channels connecting OH stakeholders, given that many informal and formal mechanisms exist and are not integrated. Interoperability challenges also arose with respect to suspected event reporting. For example, three different mobile apps are utilized to report abnormal events related to AI, and other One Health pathogens of interest, and currently these applications are unable to share data, integrated into the same data structure, or communicate with one another. A One Health challenge that emerged related to data quality and interoperability was its *security*. AI, like other zoonotic emerging infectious diseases, is of critical importance and it may be stigmatizing to report due to potential downstream control mechanisms such as flock culling and trade reporting. *Transparency* is a difficult metric to maintain in infectious disease surveillance. Data sharing channels for real-time situational awareness do not exist for immediate results sharing between One Health stakeholders. AI surveillance data is often shared at high-level stakeholder meetings dispersed across time. The stakeholder agencies, government, academic, and private, also maintain their own separate databases that are not synced or integrated to facilitate surveillance data transparency.

4. Discussion

Thailand has implemented a One Health surveillance system in four provinces to monitor AI in wild birds, poultry, and humans to strengthen country-wide and global health security. This system has engaged diverse surveillance partners from the Thai government to local villagers, and the private poultry industry effectively. Public-private partnerships is again highlighted as an asset to this surveillance system, which has demonstrated success in other surveillance systems and disease control programs across the world [47–49]. The integrated approach of this AI surveillance system has initiated the removal of the metaphorical walls between different health sectors and the sharing of critical disease surveillance data. The mapping of the system and evaluation of the system's metrics has allowed for the strategic identification of strengths and challenges to further improve the current and future integrated surveillance systems. We have identified that strengths of this piloted surveillance system are simplicity, flexibility, and acceptability. The system faces challenges related to transparency, interoperability, data quality, and security.

Thailand's AI surveillance system evaluation results were synthesized into recommendations with five areas of focus and specific aims for system strengthening (Table 2). The focus areas include: 1) strengthening surveillance reporting and communication, 2) increasing laboratory integration between human and animal sectors, 3) improving pathogen detection capabilities and flexibility, 4) implementing interoperable systems, and 5) incorporating these recommendations through sustainable capacity building mechanisms.

Surveillance data, reports, and communications from the local levels, such as villages, districts, and provinces, should be integrated up to the national level to maintain surveillance situational awareness. This unification of data and information could be achieved through a common data management system with clear corresponding guidance and quality standards. Thailand's One Health AI surveillance system could be further strengthened by increasing the integration between human and animal laboratory staff, resources, and spaces. Samples often travel long distances and human and animal health laboratories are distributed differently across the country. Laboratory collaboration or the repurposing of laboratories for integrated-animal, human, and environment pathogen monitoring, could assist in the strategic allocation of resources, decrease sample travel times, and bridge gaps between siloed staff. Another recommendation area focuses on strengthening pathogen detection capabilities, flexibility, and resilience. This surveillance system could benefit from integrating rapid and multiplexed pathogen detection technologies to improve timeliness and remain flexible to other pathogen threats apart from AI. Next-generation sequencing (NGS) platforms, especially field-able technologies, could also be used to detect influenza viruses and potentially novel viruses, in One Health surveillance sampling activities, especially in targeted hotspot locations such as live bird markets [50]. The system also currently focusses on domestic and wild avian species and humans, and it is recommended to expand influenza surveillance to swine [51,52] and potential environmental monitoring sources such as wastewater or water sources near high-risk human-animal interfaces [53]. Expanding the system will also require increased capacity and streamlined data flows. The implementation of an interoperable data system could address these needs while also improving data quality, timeliness, and transparency.

Table 2
Focus areas and recommendations for Thailand's AI Surveillance System.

Focus Area	Metrics	Recommendations
Integrate surveillance reporting and communication from the local (village, district, and province) to national levels	Acceptability Flexibility Interoperability Simplicity Transparency	• Adopt a unified One Health data management and surveillance system that integrates human, animal, and environmental health domains
Increase integration between human and animal laboratories	Acceptability Flexibility Interoperability Security Stability Simplicity Timeliness Transparency	• Integrate laboratory resources and stakeholders through a One Health approach to build collaborations; optimize laboratory space, protocols, and equipment • Build partnerships between animal, human, and environmental laboratories
Strengthen pathogen detection capabilities, flexibility, and resilience	Data Quality Flexibility Sensitivity	• Integrate rapid and multiplex pathogen detection technologies in the laboratory and the field • Increase throughput capacity of human resources, surveillance, and laboratory activities • Streamline data flow to increase surveillance capacity at local hotspots • Expand influenza surveillance to swine and potential environmental sources • Broaden pathogen detection to other critical zoonotic pathogens
Implement an interoperable data management system	Data Quality Flexibility Interoperability Sensitivity Timeliness Transparency	• Adopt a reliable, easily accessible data integration and management system to improve data repositories and interoperability of One Health surveillance data • Allow for system to be implemented in all related sectors, including government, private, intergovernmental, non-profit, and academic stakeholders
Sustainability and capacity building	Interoperability Security Transparency	• Outline and commit to shared data and hardware ownership through cooperative or data-use agreements • Devote renewable monetary funds and human resources to shared surveillance system • Ownership may consist of a primary owner the permanent location of the system, shared-ownership, or rotating ownership with specified time periods • Empower current and future workforces at all levels • Integrate technologies that support recommendations, lower burden on workforces, and improve surveillance capabilities

Electronic data integration and management would reduce the stress on workforces who hand enter and send data and would also reduce human errors. The system could also provide more real-time situational awareness to surveillance partners who would normally share data at designated meetings throughout the year. Lastly, to address challenges, grow the piloted system, and implement recommendations sustainable funding mechanisms, technology integration, and capacity building are needed. Workforce development and surveillance partnership engagement at all levels are critical surveillance strengthening elements. Thailand's pilot One Health AI surveillance system innovatively integrates pathogen detection, public health, and multidisciplinary collaboration. The system can grow its impact on global health security by maintaining the system's strengths and addressing challenges.

The limitations of the study are rooted in stakeholder sample, metric tools, and potential responder biases. The key informants that participated in semi-structured interviews were only recruited from the central level. Local provincial and district levels were not included in this sample and consequently, the local surveillance officer perspective was not included in metrics and evaluations. Another limitation derived from the lack of quantitative data for availability for sensitivity and specificity estimates. The evaluations metrics analysis also did not calculate quantitative scores as these metrics were utilized as a data collection guide and tool to identify strengths and challenges. Potential biases may have also been introduced from responder bias during stakeholder interviews, however, surveillance system components, strengths, and challenges were evaluated from a diverse stakeholder group from all involved agencies.

5. Conclusions

Thailand has integrated a One Health approach to public health through the establishment of a coordinating unit, surveillance activities, integrated trainings, and research conferences. Thailand's piloted AI surveillance system exhibits similarities to other One Health systems, such as it has focused on one priority pathogen, integrates human, livestock, and wildlife health agencies, and aims to increase degrees of collaboration across surveillance system components. However, Thailand has innovatively established a One Health specific government unit, the CUOH, within its central government structure, which is a characteristic not yet largely adopted globally. Already a global leader in its One Health advancements, Thailand's AI surveillance system may benefit from improving several focus areas, including further local level engagement, increased laboratory integration between the human and animal facets, and higher degrees of system interoperability among species and departments. Transformative technologies paired with capacity building activities can be integrated into Thailand's existing strong One Health stakeholder network to improve data interoperability, pathogen detection potential, and downstream public health actions. This One Health approach should also be expanded to enhance surveillance of other critical zoonotic pathogens, especially those with pandemic potential to strengthen global health security, and may also serve as an example for other centralized surveillance systems. Overall, Thailand's One Health AI surveillance system provides a strategic framework that can be used to develop, integrate, or bolster integrated surveillance systems—a necessary public health tool to combat global, zoonotic pathogen threats.

CRediT authorship contribution statement

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Declaration of Competing Interest

None.

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References

[1] Institute of Medicine (US) Forum on Microbial Threats, Ethical and Legal Considerations in Mitigating Pandemic Disease: Workshop Summary. 3 Strategies for Disease Containment, Washington, DC. https://www.ncbi.nlm.nih.gov/books/NBK54163/, 2007 (accessed December 15, 2020).

[2] C.L. Richards, M.F. Iademarco, D. Atkinson, R.W. Pinner, P. Yoon, W.R. Mac Kenzie, B. Lee, J.R. Qualters, T.R. Frieden, Advances in public health surveillance and information dissemination at the centers for disease control and prevention, Public Health Rep. 132 (2017) 403–410, https://doi.org/10.1177/0033354917709542.

[3] National Research Council (US) Committee on Achieving Sustainable Global Capacity for Surveillance and Response to Emerging Diseases of Zoonotic Origin, Achieving Sustainable Global Capacity for Surveillance and Response to Emerging Diseases of Zoonotic Origin: Workshop Report. 5 Laboratory and Epidemiological Capacity, National Academies Press (US), Washington, DC, 2008. https://www.ncbi.nlm.nih.gov/books/NBK208005/ (accessed December 15, 2020).

[4] L.M. Lee, S.B. Thacker, Public health surveillance and knowing about health in the context of growing sources of health data, Am. J. Prev. Med. 41 (2011) 636–640, https://doi.org/10.1016/j.amepre.2011.08.015.

[5] US Centers for Disease Control and Prevention, Epidemiology and Laboratory Capacity for Prevention and Control of Emerging Infectious Diseases (ELC), (n.d.). https://www.cdc.gov/ncezid/dpei/epidemiology-laboratory-capacity.html (accessed December 15, 2020).

[6] M.T. Osterholm, Global health security—an unfinished journey, Emerg. Infect. Dis. 23 (2017) S225–S227, https://doi.org/10.3201/eid2313.171528.

[7] W. Mwangi, P. de Figueiredo, M.F. Criscitiello, One health: addressing global challenges at the Nexus of human, animal, and environmental health, PLoS Pathog. 12 (2016) e1005731, https://doi.org/10.1371/journal.ppat.1005731.

[8] T.R. Kelly, C. Machalaba, W.B. Karesh, P.Z. Crook, K. Gilardi, J. Nziza, M.M. Uhart, E.A. Robles, K. Saylors, D.O. Joly, C. Monagin, P.M. Mangombo, P.M. Kingebeni, R. Kazwala, D. Wolking, W. Smith, J.A.K. Mazet, P. Consortium, Implementing one health approaches to confront emerging and re-emerging zoonotic disease threats: lessons from PREDICT, One Heal. Outlook. 2 (2020) 1, https://doi.org/10.1186/s42522-019-0007-9.

[9] E. O'Brien, I. Xagoraraki, A water-focused one-health approach for early detection and prevention of viral outbreaks, One Heal. (Amsterdam, Netherlands). 7 (2019) 100094, https://doi.org/10.1016/j.onehlt.2019.100094.

[10] A. Mostafa, E.M. Abdelwhab, T.C. Mettenleiter, S. Pleschka, Zoonotic potential of influenza a viruses: a comprehensive overview, Viruses. 10 (2018) 497, https://doi.org/10.3390/v10090497.

[11] J. Zinsstag, E. Schelling, K. Wyss, M.B. Mahamat, Potential of cooperation between human and animal health to strengthen health systems, Lancet (London, England). 366 (2005) 2142–2145, https://doi.org/10.1016/S0140-6736(05)67731-8.

[12] J.S. Mackenzie, M. McKinnon, M. Jeggo, One health: from concept to practice, Confronting Emerg. Zoonoses One Heal. Paradig. (2014) 163–189, https://doi.org/10.1007/978-4-431-55120-1_8.

[13] M. Bordier, T. Uea-Anuwong, A. Binot, P. Hendrikx, F.L. Goutard, Characteristics of one health surveillance systems: a systematic literature review, Prev. Vet. Med. 181 (2020), 104560, https://doi.org/10.1016/j.prevetmed.2018.10.005.

[14] J.E.B. Halliday, A.L. Meredith, D.L. Knobel, D.J. Shaw, B.M.C. de Bronsvoort, S. Cleaveland, A framework for evaluating animals as sentinels for infectious disease surveillance, J. R. Soc. Interface 4 (2007) 973–984, https://doi.org/10.1098/rsif.2007.0237.

[15] W.A. Mauer, J.B. Kaneene, Integrated human-animal disease surveillance, Emerg. Infect. Dis. 11 (2005) 1490–1491, https://doi.org/10.3201/eid1109.050180.

[16] R. Piltch-Loeb, J. Kraemer, K.W. Lin, M.A. Stoto, Public health surveillance for Zika virus: data interpretation and report validity, Am. J. Public Health 108 (2018) 1358–1362, https://doi.org/10.2105/AJPH.2018.304525.

[17] A. Zumla, O. Dar, R. Kock, M. Muturi, F. Ntoumi, P. Kaleebu, M. Eusebio, S. Mfinanga, M. Bates, P. Mwaba, R. Ansumana, M. Khan, A.N. Alagaili, M. Cotten, E.I. Azhar, M. Maeurer, G. Ippolito, E. Petersen, Taking forward a "One Health" approach for turning the tide against the Middle East respiratory syndrome coronavirus and other zoonotic pathogens with epidemic potential, Int. J. Infect. Dis. IJID Off. Publ. Int. Soc. Infect. Dis. 47 (2016) 5–9, https://doi.org/10.1016/j.ijid.2016.06.012.

[18] E.A.B. Farag, M. Nour, A. El Idrissi, J. Berrada, A. Moustafa, M. Mehmood, M. H. Mahmoud, A.M. El-Sayed, F. Alhajri, M. Al-Hajri, O.A. Hassan, H. Al-Romaihi, M. Al-Thani, S.A. Al-Marri, M.P.G. Koopmans, M.H. Ismail, Survey on implementation of one health approach for MERS-CoV preparedness and control in gulf cooperation council and Middle East countries, Emerg. Infect. Dis. 25 (2019), https://doi.org/10.3201/eid2503.171702.

[19] A. Ruckert, K. Zinszer, C. Zarowsky, R. Labonté, H. Carabin, What role for one health in the COVID-19 pandemic? Can. J. Public Heal. 111 (2020) 641–644, https://doi.org/10.17269/s41997-020-00409-z.

[20] A.D.M.E. Osterhaus, C. Vanlangendonck, M. Barbeschi, C.J.M. Bruschke, R. Christensen, P. Daszak, F. de Groot, P. Doherty, P. Drury, S. Gmacz, K. Hamilton, J. Hart, R. Katz, C. Longuet, J. McLeay, G. Morelli, J. Schlundt, T. Smith, S. Suri, K. Umali, J. van Aken, J.A. Wagenaar, Make science evolve into a One Health approach to improve health and security: a white paper, One Heal. Outlook. 2 (2020) 6, https://doi.org/10.1186/s42522-019-0009-7.

[21] R.T. de Melo, D.A. Rossi, G.P. Monteiro, H. Fernandez, Veterinarians and One Health in the fight against Zoonoses such as COVID-19, Front. Vet. Sci. 7 (2020), 576262, https://doi.org/10.3389/fvets.2020.576262.

[22] World Health Organization, The Tripartite's Commitment: Providing Multi-Sectoral, Collaborative Leadership in Addressing Health Challenges., Geneva, Switzerland. http://www.who.int/zoonoses/tripartite_oct2017.pdf?ua=1, 2017.

[23] G. Paternoster, L. Tomassone, M. Tamba, M. Chiari, A. Lavazza, M. Piazzi, A. R. Favretto, G. Balduzzi, A. Pautasso, B.R. Vogler, The degree of One Health implementation in the West Nile virus integrated surveillance in Northern Italy, 2016, Front. Public Health 5 (2017) 236, https://doi.org/10.3389/fpubh.2017.00236.

[24] Z. Batsukh, B. Tsolmon, D. Otgonbaatar, B. Undraa, A. Dolgorkhand, O. Ariuntuya, One Health in Mongolia, Curr. Top. Microbiol. Immunol. 366 (2012), https://doi.org/10.1007/82_2012_253.

[25] C.-C. King, C.-L. Kao, D.-P. Liu, M.-C. Cheng, H.-L. Yen, M.-S. Lee, C.-P. Tsai, S.-R. Shih, H.K. Shieh, J.-P. Hsiu, S.-F. Li, H.-Y. Chen, H.-M. Hsu, S.-J. Twu, N.J. Cox, R.G. Webster, Seven integrated influenza surveillance systems in Taiwan, Int. Congr. Ser. 1219 (2001) 107–118, https://doi.org/10.1016/S0531-5131(01)00331-4.

[26] A.S. Arafa, M.M. Naguib, C. Luttermann, A.A. Selim, W.H. Kilany, N. Hagag, A. Samy, A. Abdelhalim, M.K. Hassan, E.M. Abdelwhab, Y. Makonnen, G. Dauphin, J. Lubroth, T.C. Mettenleiter, M. Beer, C. Grund, T.C. Harder, Emergence of a novel cluster of influenza A(H5N1) virus clade 2.2.1.2 with putative human health impact in Egypt, 2014/15., Euro Surveill. Bull. Eur. Sur Les Mal. Transm. = Eur. Commun, Dis. Bull. 20 (2015) 2–8, https://doi.org/10.2807/1560-7917.es2015.20.13.21085.

[27] D.S. Fedson, Influenza, evolution, and the next pandemic, Evol. Med. Public Heal. 2018 (2018) 260–269, https://doi.org/10.1093/emph/eoy027.

[28] B.E. Young, M. Chen, Influenza in temperate and tropical Asia: a review of epidemiology and vaccinology, Hum. Vaccin. Immunother. 16 (2020) 1659–1667, https://doi.org/10.1080/21645515.2019.1703455.

[29] H. Office of the Assistant Secretary for Preparedness, Pandemic Influenza Plan - Update IV (December 2017), 2017.

[30] Preventing the next pandemic, Bull. World Health Organ. 99 (2021) 326–327, https://doi.org/10.2471/BLT.21.020521.

[31] T. Chotpitayasunondh, K. Ungchusak, W. Hanshaoworakul, S. Chunsuthiwat, P. Sawanpanyalert, R. Kijphati, S. Lochindarat, P. Srisan, P. Suwan, Y. Osotthanakorn, T. Anantasetagoon, S. Kanjanawasri, S. Tanupattarachai, J. Weerakul, R. Chaiwirattana, M. Maneerattanaporn, R. Poolsavathitikool, K. Chokephaibulkit, A. Apisarnthanarak, S.F. Dowell, Human disease from influenza A (H5N1), Thailand, Emerg. Infect. Dis. 11 (2005) (2004) 201–209, https://doi.org/10.3201/eid1102.041061.

[32] World Health Organization, Cumulative Number of Confirmed Human Cases for Avian Influenza A(H5N1) Reported to WHO, 2015–2019. https://cdn.who.int/media/docs/default-source/influenza/h5n1-human-case-cumulative-table/2021_april_tableh5n1.pdf?sfvrsn=fc40672c_5&download=true, 2021 (accessed April 13, 2022).

[33] S. Heft-Neal, F. Kahrl, J. Otte, D. Roland-Holst, HPAI Risk Reduction and Smallholder Poultry Supply Chains – The Case of Thailand. http://r4d.dfid.gov.uk/Output/180394/, 2009.

[34] J. Rushton, R. Viscarra, E. Guerne Bleich, A. Mcleod, Impact of avian influenza outbreaks in the poultry sectors of five South East Asian countries (Cambodia, Indonesia, Lao PDR, Thailand, Viet Nam) outbreak costs, responses and potential long term control, Worlds. Poult. Sci. J. 61 (2005) 491–514, https://doi.org/10.1079/WPS200570.

[35] P. Auewarakul, The Past and Present Threat of Avian Influenza in Thailand, Emerg. Infect. Asia. (2008) 31–44, https://doi.org/10.1007/978-0-387-75722-3_2.

[36] A. Delabouglise, N. Antoine-Moussiaux, D. Tatong, A. Chumkaeo, A. Binot, G. Fournié, E. Pilot, W. Phimpraphi, S. Kasemsuwan, M.C. Paul, R. Duboz, G. Salem, M. Peyre, Cultural practices shaping zoonotic diseases surveillance: the case of highly pathogenic avian influenza and Thailand native chicken farmers, Transbound. Emerg. Dis. 64 (2017) 1294–1305, https://doi.org/10.1111/tbed.12506.

[37] A. Sommanustweechai, S. Iamsirithaworn, W. Patcharanarumol, W. Kalpravidh, V. Tangcharoensathien, Adoption of one health in Thailand's national strategic plan for emerging infectious diseases, J. Public Health Policy 38 (2017) 121–136, https://doi.org/10.1057/s41271-016-0053-9.

[38] R.R. German, L.M. Lee, J.M. Horan, R.L. Milstein, C.A. Pertowski, M.N. Waller, Updated guidelines for evaluating public health surveillance systems: recommendations from the guidelines working group, MMWR. Recomm. Reports Morb. Mortal. Wkly. Report. Recomm. Reports. 50 (2001) 1–7.

[39] A.A. da Silva, A.M.S. da Teixeira, C.M.A.S. Domingues, R.M. Braz, C.M. Cabral, Evaluation of the National Immunization Program Surveillance System - Vaccination Record Module, Brazil, 2017, Epidemiol. e Serv. Saude Rev. Do Sist. Unico Saude Do Bras. 30 (2021), e2019596, https://doi.org/10.1590/S1679-49742021000100028.

[40] E.B. Laryea, J.A. Frimpong, C.L. Noora, J. Tengey, D. Bandoh, G. Sabblah, D. Ameme, E. Kenu, K. Amponsa-Achiano, Evaluation of the adverse events following immunization surveillance system, Ghana, 2019, PLoS One 17 (2022), e0264697, https://doi.org/10.1371/journal.pone.0264697.

[41] Y. Khader, M. Alyahya, Z. El-Khatib, A. Batieha, N. Al-Sheyab, K. Shattnawi, The Jordan stillbirth and neonatal mortality surveillance (JSANDS) system: evaluation study, J. Med. Internet Res. 23 (2021), e29143, https://doi.org/10.2196/29143.

[42] L.S. Anam, M.M. Badi, M.A. Assada, A.A. Al Serouri, Evaluation of two malaria surveillance systems in yemen using updated CDC guidelines: lessons learned and future perspectives, Inquiry. 56 (2019), https://doi.org/10.1177/0046958019880736, 46958019880736.

[43] L. Yang, C. Weston, C. Cude, L. Kincl, Evaluating Oregon's occupational public health surveillance system based on the CDC updated guidelines, Am. J. Ind. Med. 63 (2020) 713–725, https://doi.org/10.1002/ajim.23139.

[44] S.L. Groseclose, D.L. Buckeridge, Public health surveillance systems: recent advances in their use and evaluation, Annu. Rev. Public Health 38 (2017) 57–79, https://doi.org/10.1146/annurev-publhealth-031816-044348.

[45] S. Hinjoy, A. Wongkumma, S. Kongyu, P. Smithsuwan, P. Suangtho, T. Yingyong, S. Chanvatik, S. Colombe, An assessment of epidemiology capacity in a one health team at the provincial level in Thailand, Vet. Sci. 3 (2016) 30, https://doi.org/10.3390/vetsci3040030.

[46] T. Yano, S. Phornwisetsirikun, P. Susumpow, S. Visrutaratna, K. Chanachai, P. Phetra, W. Chaisowwong, P. Trakarnsirinont, P. Hemwan, B. Kaewpinta, C. Singhapreecha, K. Kreausukon, A. Charoenpanyanet, C.S. Robert, L. Robert, P. Rodtian, S. Mahasing, E. Laiya, S. Pattamakaew, T. Tankitiyanon, C. Sansamur, L. Srikitjakarn, A participatory system for preventing pandemics of animal origins: Pilot study of the participatory one health disease detection (PODD) system, JMIR Public Heal. Surveill. 4 (2018), e25, https://doi.org/10.2196/publichealth.7375.

[47] C. Lourenço, A.J. Tatem, P.M. Atkinson, J.M. Cohen, D. Pindolia, D. Bhavnani, A. Le Menach, Strengthening surveillance systems for malaria elimination: a global landscaping of system performance, 2015-2017, Malar. J. 18 (2019) 315, https://doi.org/10.1186/s12936-019-2960-2.

[48] H. Bashier, A. Ikram, M.A. Khan, M. Baig, M. Al Gunaid, M. Al Nsour, Y. Khader, The anticipated future of public health services post COVID-19: viewpoint, JMIR Public Heal. Surveill. 7 (2021), e26267, https://doi.org/10.2196/26267.

[49] R.K. Phalkey, M. Kroll, S. Dutta, S. Shukla, C. Butsch, E. Bharucha, F. Kraas, Knowledge, attitude, and practices with respect to disease surveillance among urban private practitioners in Pune, India, Glob. Health Action 8 (2015) 28413, https://doi.org/10.3402/gha.v8.28413.

[50] J. Zhao, V. Ragupathy, J. Liu, X. Wang, S.V. Vemula, H.S. El Mubarak, Z. Ye, M. L. Landry, I. Hewlett, Nanomicroarray and multiplex next-generation sequencing for simultaneous identification and characterization of influenza viruses, Emerg. Infect. Dis. 21 (2015) 400–408, https://doi.org/10.3201/eid2103.141169.

[51] W. Thanapongtharm, C. Linard, P. Chinson, S. Kasemsuwan, M. Visser, A. E. Gaughan, M. Epprech, T.P. Robinson, M. Gilbert, Spatial analysis and characteristics of pig farming in Thailand, BMC Vet. Res. 12 (2016) 218, https://doi.org/10.1186/s12917-016-0849-7.

[52] W. Ma, R.E. Kahn, J.A. Richt, The pig as a mixing vessel for influenza viruses: human and veterinary implications, J. Mol. Genet. Med. 3 (2008) 158–166. https://pubmed.ncbi.nlm.nih.gov/19565018.

[53] L. Heijnen, G. Medema, Surveillance of influenza a and the pandemic influenza A (H1N1) 2009 in sewage and surface water in the Netherlands, J. Water Health 9 (2011) 434–442, https://doi.org/10.2166/wh.2011.019.