Chinese Industry and Technology of Eco-environment
2026, VOL. 7, NO. 1, 33-37
DOI: 10.47297/wspciateWSP2633-772X06.20260701

Laws of Avian Influenza Cross-Species Spillover and Its Reference Value for Human Public Health Early Warning System

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ABSTRACT
Avian influenza viruses can cross species barriers and transmit to humans, triggering severe public health crises. Exploring the laws of its cross-species spillover and the reference value for human public health early warning systems is of important practical significance for epidemic prevention and control as well as public health security guarantee. This paper systematically sorts out the core laws of avian influenza cross-species spillover, identifies two key characteristics of host-driven effect and genetic variation adaptation. It further explores the reference essentials for human public health early warning systems from three dimensions: collaborative monitoring, response mechanism construction and capacity improvement. On this basis, targeted preventive measures are proposed from the perspectives of network monitoring, response procedure and support system construction based on the public health early warning system. It aims to improve the quality of human public health early warning work under the background of avian influenza cross-species spillover, and lay a foundation for formulating more effective preventive strategies.

KEYWORDS
Avian influenza; Cross-species spillover; Human public health early warning

1 Introduction

Avian influenza is an acute infectious disease caused by influenza A viruses. It is predominantly hosted by avians and can cross species barriers to infect humans, triggering public health crises and causing substantial economic losses. In recent years, the frequency of cross-species spillover events of multiple avian influenza subtypes has been continuously rising, resulting in heavy losses to the poultry breeding industry. Human infections often lead to severe symptoms such as high fever and pneumonia with an extremely high case fatality rate. In the process of potential human-to-human transmission, additional underlying risks may also emerge. This phenomenon breaks conventional cognitive perceptions and exposes shortcomings in the human public health early warning system. Therefore, it is critical to further explore the spillover mechanisms, explore its reference implications, and establish an effective defense system. The construction of an early warning system requires comprehensive consideration of multiple influencing factors and precise risk identification, so as to provide support for further optimizing the prevention and control efficacy of avian influenza cross-species spillover.

2 Analysis on the Laws of Avian Influenza Cross-Species Spillover

2.1 Host-Driven Law

The cross-species spillover of avian influenza viruses is not a random event. Instead, it relies on specific hosts to form a transmission chain linking natural reservoirs, intermediate hosts and humans. Wild waterfowl, domestic poultry and some mammals serve as important carriers driving the cross-species transmission of viruses. Wild waterfowl act as the natural reservoir of avian influenza viruses, carrying multiple influenza subtypes mostly in latent infection status. Their migratory behavior enables transboundary viral spread, making them a key source of cross-species transmission[1]. Relevant studies have shown that migratory routes of wild waterfowl such as anatids and gulls cover major regions worldwide. Viruses can contaminate water sources through fecal secretions, and further pollute surrounding soil and ecological environments, thereby spreading to residential populations.

In this process, domestic poultry function as vital intermediate hosts with high susceptibility to avian influenza viruses. Infected poultry develop obvious clinical symptoms, within which the virus replicates and mutates rapidly, enhancing its capacity for cross-species transmission. Furthermore, recent studies have found that mammals including pigs, cats and dairy cows can also serve as intermediate hosts for avian influenza viruses. Notably, pigs possess receptors for both avian and human influenza viruses, acting as a mixing vessel for viral genetic reassortment. This facilitates viral mutation, improves viral adaptability to humans, and elevates the risk of cross-species spillover.

2.2 Mutation and Adaptation Law

Genetic mutation and reassortment of avian influenza viruses are key determinants of their cross-species transmission, with mutation, adaptation and transmission forming a progressive linkage. As single-stranded RNA viruses, avian influenza viruses have unstable genomic structures and are prone to base mismatches during replication. Meanwhile, when different viral subtypes co-infect the same host, genetic segment reassortment may occur, generating novel recombinant strains. Such genetic variations are mainly concentrated in key proteins such as hemagglutinin (HA) and

neuraminidase (NA).

The HA protein is primarily responsible for recognizing host cell receptors; its genetic mutations may alter viral host specificity, enabling the virus to bind to cell receptors of humans and other mammals and achieve cross-species infection. For instance, genetic mutations of the H5N1 avian influenza subtype markedly enhance its affinity for human respiratory epithelial cells, increasing the risk of human infection. Existing research indicates that the mutation of the 115th amino acid of the avian influenza M1 protein from valine to isoleucine can strengthen the virus's antagonism against human immune barriers, boost its proliferation ability in human cells, and consequently promote avian influenza cross-species spillover. The pathogenicity of avian influenza viruses may also complicate epidemic containment after spillover, which constitutes a major driver of the normalized trend of avian influenza cross-species spillover[2].

3 Reference Value of Avian Influenza Cross-Species Spillover for Human Public Health Early Warning System

3.1 Construction of the "Human-Avian-Environment" Collaborative Monitoring Model

The concealment and diffusivity of avian influenza cross-species spillover have raised higher requirements for the monitoring capacity of the human public health early warning system. Its core reference value lies in promoting the transformation of early warning monitoring from single human-oriented monitoring to collaborative monitoring integrating humans, poultry and the environment, so as to realize full-chain and all-round risk perception.

At present, most human public health early warning systems focus on the monitoring and reporting of human cases, while attaching insufficient importance to the surveillance of animal epidemics and environmental viral contamination. This leads to the failure of timely detection in the early stage of avian influenza cross-species spillover and misses the optimal prevention and control window[3]. The monitoring practice of avian influenza cross-species spillover indicates that viral transmission originates from animal populations, spreads mainly through environmental media, and may eventually infect humans.

Therefore, it is necessary to construct a collaborative monitoring model to improve the timeliness of early warning. Drawing on the monitoring experience of avian influenza prevention and control, the human public health early warning system should break departmental barriers, strengthen cooperation with agriculture, forestry, environmental protection and other departments, and establish a monitoring network covering key sites such as breeding bases, poultry farms, live poultry markets and slaughterhouses. Meanwhile, high-risk groups including medical staff, breeders and slaughter workers should be incorporated into the monitoring network, integrating active monitoring, passive monitoring and sentinel monitoring. Synchronous monitoring of poultry epidemics, environmental viral contamination and suspected human cases shall be implemented to realize real-time sharing and linkage analysis of monitoring data[4].

3.2 Establishment of a Graded, Classified and Rapidly Linked Response Model

Epidemics caused by avian influenza cross-species spillover differ significantly in severity and transmission speed, and their prevention and control practices provide effective references for optimizing the response mechanism of the human public health early warning system. The core reference value is to establish a graded, classified and rapidly linked early warning response model, so as to enhance the targeted effectiveness and efficiency of emergency disposal.

In some regions, the current early warning response for zoonotic diseases is characterized by delayed response, homogeneous countermeasures and poor inter-departmental coordination, which cannot meet the prevention and control requirements of cross-species infectious diseases. In the prevention and control of avian influenza cross-species spillover, epidemics are classified into different grades according to viral subtypes, infection scope, pathogenicity and other factors, with targeted prevention and control measures adopted correspondingly. For example, mandatory measures such as blockade, culling and disinfection shall be promptly implemented for highly pathogenic avian influenza epidemics; for newly confirmed epidemic monitoring priorities, monitoring and control intensity should be intensified to curb epidemic spread.

Drawing on this experience, the human public health early warning system shall improve the early warning grading standards, clearly divide early warning levels by combining indicators such as cross-species transmission risk, pathogenicity and transmission speed of infectious diseases, and clarify the responsible subjects, response measures and time limits for each level. In addition, an inter-departmental linkage response mechanism should be established to define the division of responsibilities among health, agriculture and rural affairs, forestry and grassland, emergency management and other departments. This ensures that all departments can respond rapidly, cooperate closely, and promptly carry out a series of work including virus investigation and tracing after the release of early warning information. Moreover, following the principle of early detection, early reporting, early isolation and early treatment adopted in avian influenza prevention and control, the response process should be optimized to shorten the response time, effectively contain the transmission chain at the initial stage of the epidemic, and reduce the risk of epidemic spread.

3.3 Consolidation of the Support System for Technology, Resources and Public Participation

The prevention and control of avian influenza cross-species spillover relies on strong technical and resource support, and public participation also plays an indispensable role, which provides important reference implications for the

capacity building of the human public health early warning system. It is essential to strengthen technological research and development, resource reserve and public mobilization, and build a comprehensive early warning support system.

First of all, in terms of technical support, the prevention and control of avian influenza cross-species spillover has driven the development of virus detection, gene sequencing, vaccine development and other technologies. By reference, the construction of the human public health early warning system should increase investment in technological research and development, focusing on the development of rapid detection technology, gene sequencing technology and risk assessment technology for cross-species infectious diseases, so as to improve the accuracy of epidemic early warning and predict transmission risks in advance.

In terms of resource guarantee, a sound material reserve system should be established with full preparation of vaccines, disinfection supplies, protective equipment and other materials, ensuring rapid allocation of various resources once an epidemic occurs. The human public health early warning system should also follow this practice, establish and improve the resource reserve system for the prevention and control of cross-species viruses, clarify reserve categories, quantity and allocation procedures, and strengthen the dynamic management and timely renewal of materials to fully meet emergency demands.

In terms of public participation, health education is adopted in avian influenza prevention and control to raise public awareness of epidemic prevention and self-protection capability. Similarly, the human public health early warning system should attach importance to public mobilization, carry out health education through multiple channels, popularize knowledge on the prevention and control of cross-species infectious diseases, and guide the public to actively cooperate with monitoring and reporting and fully implement epidemic prevention and control work[5].

4 Preventive Measures Against Avian Influenza Cross-Species Spillover Based on Public Health Early Warning System

4.1 Constructing a Collaborative Monitoring Network to Consolidate the Pre-Early Warning Defense Line

For prevention and control based on the public health early warning system, the primary task is to build a trinity collaborative monitoring network covering humans, poultry and the environment. It conducts all-round and whole-chain monitoring of avian influenza cross-species spillover, consolidates the pre-early warning defense line, and provides strong support for early detection and early warning.

The construction of the monitoring network should break institutional barriers and establish a multi-department collaborative working mechanism involving health, agriculture and rural affairs, and other relevant authorities. Clarify the division of monitoring responsibilities among all departments to realize real-time sharing, linkage analysis and unified judgment of monitoring data.

First, in terms of poultry monitoring, it is necessary to strengthen surveillance at key sites including habitats of wild waterfowl, large-scale poultry farms, live poultry markets and slaughterhouses. Samples such as serum, throat swabs and feces are collected from poultry for viral nucleic acid testing and serological detection, so as to detect epidemic infections in a timely manner. Live poultry markets shall strictly implement the regulation of daily disinfection and weekly inspection to dynamically monitor environmental viral contamination. Once positive samples are identified, early warning shall be activated immediately and targeted control measures shall be adopted without delay.

In terms of population monitoring, relying on the sentinel hospital network of the public health early warning system, surveillance should be intensified for suspected cases with symptoms such as fever, cough and dyspnea, with priority screening for high-risk populations with a history of poultry exposure. Nucleic acid testing shall be promptly arranged for suspected cases to ensure early detection and early reporting.

As for environmental monitoring, regular comprehensive detection shall be carried out on water sources, soil and atmospheric environment surrounding poultry breeding sites, live poultry markets and slaughterhouses, so as to clarify the status of viral contamination and trace viral transmission routes. To clearly present the composition of the monitoring network and the division of responsibilities and provide reference basis, the key monitoring points of different units are shown in Table 1.

Table 1 Key Points of Monitoring Work in Different Links

Monitoring Subject	Monitoring Objects	Monitoring Contents	Responsible Departments
Poultry Monitoring Unit	Wild waterfowl, domestic poultry, mammalian intermediate hosts	Viral infection status, viral subtypes, genetic variation	Bureau of Agriculture and Rural Affairs, Forestry and Grassland Bureau
Human Monitoring Unit	High-risk groups, suspected cases, close contacts	Fever and other clinical symptoms, viral nucleic acid test results, infection status	Health Commission
Environmental Monitoring Unit	Water sources, soil, air, environment of breeding and trading sites	Viral contamination status, pollution scope, transmission routes	Ecology and Environment Bureau, Bureau of Agriculture and Rural Affairs
Comprehensive Evaluation Unit	Various monitoring data, epidemic dynamics	Risk assessment, early warning grading, prevention and control suggestions	Joint participation of multiple departments including Health Commission and Bureau of Agriculture and Rural Affairs

4.2 Optimize Early Warning Response Process and Improve Emergency Disposal Efficiency

Relying on the public health early warning system, optimizing the early warning response process for avian influenza cross-species spillover and establishing a graded, classified and rapidly linked emergency disposal mechanism play a crucial role in improving defense efficiency. Such arrangements enable rapid response, scientific disposal and containment of viral transmission once an epidemic emerges.

First, it is necessary to refine the early warning grading criteria. Combined with the subtype, pathogenicity, infection scope, transmission speed and cross-species transmission risk of avian influenza viruses, early warnings can be divided into four levels: general, moderate, severe, and extremely severe. The activation conditions, response measures and time limits corresponding to each level should be clearly defined to avoid over-response or inadequate response.

Furthermore, a unified early warning information release platform should be established in accordance with the early warning release mechanism, clarifying the releasing authority, release channels and specific content. This ensures that early warning information can be rapidly and accurately transmitted to all relevant departments, institutions and the public, so as to mobilize multiple stakeholders to implement targeted prevention and control measures. Meanwhile, a dynamic update mechanism for early warning information shall be formulated to adjust warning levels and released content in line with epidemic evolution.

In addition, the inter-departmental linkage response mechanism should be strengthened by clarifying the division of responsibilities among health authorities, forestry and grassland administrations, emergency management departments and other relevant agencies, so as to form a coordinated working system after the issuance of early warning information.

The Bureau of Agriculture and Rural Affairs is mainly responsible for timely handling poultry epidemics, culling infected poultry, and conducting disinfection of breeding farms. Health authorities focus on screening human cases, tracing close contacts, implementing isolation medical observation, and arranging relevant medical treatment. Market supervision departments strengthen the regulation of live poultry markets and suspend live poultry trading. Emergency management departments undertake material allocation and logistical support after public health emergencies.

After the completion of epidemic disposal, a comprehensive evaluation of the entire response process and the implementation effect of relevant measures should be conducted. On this basis, the response process can be continuously improved to enhance the overall quality of emergency disposal (see Figure 1).



Figure 1 Flowchart of Early Warning Response to Avian Influenza Cross-Species Spillover

4.3 Strengthen the Construction of Support System and Consolidate the Foundation of Prevention Work

To enhance the support capacity of the public health early warning system, targeted measures should be taken from three dimensions: technology, resources, and public participation. This ensures the effective implementation of preventive strategies against avian influenza cross-species spillover and provides comprehensive guarantee for early warning surveillance and emergency response.

In terms of technical support, it is necessary to increase investment in scientific research, focusing on the research and development of rapid detection technology, gene sequencing technology, and risk assessment technology for avian influenza viruses. New technologies such as third-generation nanopore sequencing should be promoted and applied to shorten detection time and improve detection accuracy. Meanwhile, cooperation with scientific research institutions should be strengthened to further explore the mechanisms underlying avian influenza cross-species spillover. In addition,

a gene bank and database for avian influenza viruses can be established to integrate global viral variation data and strengthen the monitoring and analysis of viral mutations. This enables early prediction of transmission risks and provides a theoretical basis for vaccine development and the formulation of prevention and control measures.

From the perspective of resource guarantee, a comprehensive emergency material reserve system should be established, clarifying reserve categories, reserve quantities, and basic allocation procedures. Dynamic management and regular renewal of materials should be further strengthened to ensure the rapid deployment of sufficient vaccines once an epidemic occurs. On this basis, investment in public health should be increased, public health infrastructure improved, and the detection and emergency disposal capacity of sentinel hospitals and monitoring institutions enhanced. Talent team construction should also be advanced by cultivating interdisciplinary professionals with comprehensive knowledge of public health, veterinary medicine, microbiology and related disciplines, so as to elevate the overall professional level of surveillance, early warning and emergency response.

Public participation mainly relies on the publicity channels of the public health early warning system to carry out health education on avian influenza prevention and control. It popularizes knowledge concerning viral transmission routes, preventive measures and suspected clinical symptoms, thereby improving public awareness of epidemic prevention and self-protection capability. Furthermore, a public reporting mechanism should be established to encourage the public to report abnormal poultry deaths and suspected cases, forming an atmosphere of joint prevention and control with nationwide participation. Specialized training should be further strengthened for high-risk groups to cultivate their awareness of self-protection and emergency response capability. The key points of support system construction are presented in Table 2.

Table 2 Key Information for the Construction of the Support System

Dimension of Support	Specific Measures	Responsible Entities
Technical Support	1. Develop technologies for rapid detection, gene sequencing, and risk assessment; 2. Study the mechanisms of viral cross-species spillover and identify molecular markers; 3. Establish a viral gene bank and database to monitor viral mutations; 4. Promote the application of new monitoring and detection technologies.	Health authorities, research institutions, and universities
Resource Support	1. Establish an emergency material reserve system and standardize material management and allocation; 2. Increase investment in public health and improve infrastructure construction; 3. Cultivate interdisciplinary prevention and control talents to enhance professional capabilities; 4. Establish a cross-regional material allocation mechanism.	Health authorities, emergency management departments, and finance departments
Public Participation	1. Conduct multi-channel health education to popularize prevention and control knowledge; 2. Establish a public reporting mechanism to encourage participation in epidemic surveillance; 3. Provide specialized training for high-risk groups to improve their protective capabilities; 4. Guide the public to cooperate with prevention and control measures and foster an atmosphere of joint prevention and control.	Health authorities, community residents' committees, and relevant enterprises

5 Conclusion

Based on the comprehensive analysis of this paper, the cross-species spillover of avian influenza is affected by multiple factors and presents two core laws: host-driven transmission and genetic variation adaptation. The frequent occurrence of such spillover events not only endangers the development of the poultry breeding industry, but also poses a serious threat to human health and public health security. In-depth exploration of the inherent laws of avian influenza cross-species spillover, clarification of its reference value, and establishment of a sound prevention system can facilitate the analysis of construction strategies for defensive frameworks based on the key points of the development and application of human public health early warning systems, so as to propose more targeted and effective preventive countermeasures.

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