Biomedical Testing & Sensing
2026, VOL. 5, NO. 1, 27-32
DOI: 10.47297/wspbtsWSP2755-952106.20260501

Population Infection Risk and Whole-process Health Management Strategy of Vaccines Regarding Pigs as Mixers of Influenza A Virus

Weiye Ou

Zhejiang MEBOLO Biotechnology CO.,Ltd, Jinhua, Zhejiang, 321000, China

ABSTRACT
Pigs simultaneously express both α-2,3 and α-2,6 sialic acid receptors in their respiratory tracts, which enables them to be co-infected by avian-origin, human-origin and swine-origin influenza A viruses and facilitate viral genetic reassortment. Therefore, pigs are recognized as the mixing vessel of influenza viruses and play a crucial role in the origin and cross-species transmission of novel pandemic influenza strains. This paper systematically elaborates the three internal logical mechanisms of pigs serving as the mixing vessel of influenza A viruses. It further identifies typical population infection risks from four dimensions: occupational exposure, pathogenicity of recombinant strains, community transmission and potential pandemic threats. On this basis, this paper proposes whole-process health management strategies covering the research and development as well as production of vaccines, cold chain storage and transportation, on-site vaccination, and vaccine waste disposal and subsequent treatment. The objective is to improve the quality of infection prevention and control through standardized and effective health management.

KEYWORDS
Influenza a virus; Population infection; Vaccine; Health management

1 Introduction

Influenza A virus can cause zoonotic diseases and serves as a critical pathogen triggering global pandemics. As a natural viral mixing vessel, pigs are susceptible to influenza A viruses of avian, human and swine origins. Co-infection and genetic reassortment constitute the core mechanism for the emergence of novel viral strains. In recent years, swine-origin influenza A viruses such as G4 EA H1N1 and recombinant H3N2 have continuously caused human infections, posing growing health risks to occupationally exposed populations and the general public, which has become a major global public health concern.

Existing studies mainly focus on viral molecular mechanisms and epidemiological investigations, while research on the integrated prevention and control system covering mixing vessel mechanism – human infection risk – whole-process vaccine health management remains insufficient. How to optimize vaccine health management quality and improve epidemic prevention and control efficacy through effective whole-process health management has become a key research issue to be addressed.

2 Internal Logic of Pigs as the Mixing Vessel of Influenza A Virus

2.1 Host Cellular Basis for Pigs Becoming a Mixing Vessel

Porcine respiratory epithelial cells simultaneously express α-2,3-linked and α-2,6-linked sialic acid receptors. The former is the primary binding target for avian-origin influenza A viruses, whereas the latter serves as the dominant binding site for human-origin influenza A viruses. This dual-receptor distribution enables pigs to be invaded and replicated by influenza viruses of avian, human and swine origins simultaneously, providing an essential cellular microenvironment for viral co-infection and genetic reassortment.

As the natural gene reservoir of influenza A viruses, wild waterfowl can transmit viruses to pig populations via feces, water sources and other routes. Human seasonal influenza viruses can spill over into pig herds through occupational contact. Classical swine influenza viruses circulate persistently among pigs. The co-circulation of multiple-origin viruses in the same pig population provides a stable host environment for gene segment exchange within individual pigs and even within single cells, which constitutes the core biological basis that distinguishes pigs from other poultry as an ideal viral mixing vessel.

2.2 Core Mechanism for the Generation of Novel Recombinant Strains

Influenza A virus possesses a segmented RNA genome consisting of 8 gene segments. When a single cell is co-infected by two or more viral subtypes or strains of different origins, progeny viruses can randomly package gene segments from different parental viruses, resulting in genetic reassortment and antigenic shift. This is the major pathway for the emergence of novel pandemic strains.

The efficient replication microenvironment and immune pressure in porcine bodies accelerate viral mutation and recombinant screening, enabling some reassortant strains to acquire key adaptive traits such as enhanced binding affinity to human receptors, higher transmissibility and increased pathogenicity. The 2009 pandemic H1N1 strain was a typical triple-reassortant virus incorporating gene segments from avian, human and swine influenza viruses. Its origin was directly linked to viral reassortment in pigs, confirming the decisive role of pigs as a reassortment platform in shaping the global influenza epidemic pattern.

2.3 Pigs as the Transmission Hub Linking Avian, Swine and Human Populations

Pigs act as an intermediate amplification node in the cross-species transmission chain of influenza A viruses. On the one hand, they facilitate the adaptation and replication of low-pathogenic avian viruses in mammals and lower the barrier of cross-species transmission. On the other hand, they introduce human-origin viruses into animal populations and expand the scope of viral circulation. Meanwhile, reassortant swine-origin viruses with enhanced human infectivity can spill back to humans, forming a complete transmission loop among birds, pigs and humans.

Occupationally exposed groups, including farm workers, slaughterhouse staff and veterinarians, are at high risk of zoonotic spillover due to long-term direct contact with pigs. Some human-adapted recombinant strains may further cause limited community transmission, and in severe cases, establish sustained human-to-human transmission chains, triggering regional epidemics or even global pandemics. It fully reflects the potential threat of pigs as a transmission bridge to public health.

3 Population Infection Risks of Pigs as Mixing Vessels of Influenza A Virus

3.1 Occupational Exposure Risk

Occupationally exposed populations working in pig farms, slaughterhouses and livestock markets, as well as veterinarians, are in long-term close contact with diseased or virus-carried pig herds, their secretions, excreta and contaminated environments. Such groups have a significantly higher infection risk of swine-origin influenza A viruses than the general public.

Pig herds usually present a high rate of latent infection with a long viral shedding cycle and atypical clinical symptoms, making early precise identification difficult. The virus can invade the human body through respiratory droplets and aerosol contact, causing fever, cough, pneumonia and other clinical manifestations, and may progress to severe pneumonia and respiratory failure in critical cases.

Serological epidemiological investigations have shown that the positive rate of antibodies against swine-origin influenza viruses among occupational groups is several times higher than that of ordinary residents, accompanied by the risk of repeated infection. Multiple subtype infections are prominent, which constitutes the main breakthrough for the spillover and spread of swine-origin viruses to human populations and also the primary driving factor of occupational exposure risks.

3.2 Pathogenic Risk of Recombinant Strains

Novel recombinant influenza viruses generated in pigs undergo substantial antigenic variation, resulting in low pre-existing herd immunity in humans. Such strains are more likely to cause severe infection and even death. Some recombinant viruses exhibit enhanced invasiveness toward human lower respiratory epithelial cells, triggering intense inflammatory responses and pulmonary tissue damage, which may lead to severe pneumonia, acute respiratory distress syndrome, and even multiple organ failure in severe cases.

They pose a prominent threat to vulnerable populations including the elderly, infants, pregnant women and patients with underlying diseases. Compared with conventional seasonal influenza, infections caused by swine-origin recombinant strains present higher hospitalization rate, severe case rate and mortality rate, while targeted specific therapeutic drugs remain limited. This imposes enormous pressure on clinical treatment and public health emergency response.

3.3 Community Diffusion Risk

Certain swine-origin influenza A viruses can acquire limited human-to-human transmissibility and may trigger cluster outbreaks in enclosed settings such as families, schools and factories. Transmission chains often start from occupational exposure within households and then gradually spread to communities.

Since the clinical symptoms of swine-origin influenza infection are similar to those of common cold and seasonal

influenza, early differential diagnosis is challenging, easily leading to misdiagnosis and missed diagnosis. Consequently, the source of infection cannot be isolated timely, enabling silent viral transmission within communities.

Meanwhile, the virus may undergo continuous mutation and adaptive evolution during human transmission, further improving its transmissibility and expanding the epidemic coverage, which simultaneously increases the difficulty of prevention and control as well as social health costs.

3.4 Potential Pandemic Risk

As natural mixing vessels for influenza A viruses, pigs continuously generate genetically diverse recombinant strains. Once a strain possesses high human-to-human transmissibility, strong pathogenicity and general population susceptibility, it will break geographical and species barriers and trigger large-scale influenza epidemics.

Many historical influenza pandemics are directly associated with swine-origin recombinant strains. Currently, global livestock breeding is developing toward intensification, with frequent human mobility and complex ecological environments, which further accelerates viral transmission and evolutionary adaptation, raising the risk of emergence and long-term persistence of novel pandemic strains.

Such events may cause mass human infections, medical resource crowding, disruption of social operation, and incalculable health losses and economic impacts, constituting a major potential public health crisis for mankind.

4 Whole-Process Vaccine Management Strategy Based on Risk Prevention

4.1 Health Management in Vaccine Research, Development and Production

Health management during vaccine research, development and production should be implemented from four core dimensions: accurate strain matching, controllable biosafety, full-process sterility assurance and regulatory compliance, so as to establish a sound health management system from the source.

In strain screening, a dynamic monitoring network for swine-origin influenza A viruses should be established, covering high-risk areas such as large-scale pig farms, slaughterhouses and livestock trading markets. Epidemic strain gene sequences and antigenic characteristics should be continuously collected. Priority should be given to selecting seed strains with high matching degree to local prevailing strains, strong immunogenicity and satisfactory safety, ensuring that vaccine-induced antibodies provide broad-spectrum cross-protection against immune escape caused by recombinant strain diversity.

The production environment shall strictly comply with veterinary GMP standards, with zoning into clean areas, semi-contaminated areas and contaminated areas. Personnel flow, material flow and airflow shall follow a one-way route to avoid cross-contamination.

Physical isolation shall be implemented among virulent operation areas, cell culture areas and vaccine preparation areas, equipped with independent negative pressure ventilation and high-efficiency air filtration systems to prevent the spread of production viruses and environmental microorganisms.

Full-chain traceability shall be implemented for raw material control. Seed viruses shall be preserved under low temperature with double-person and double-lock management, and complete archives shall be established for passage, identification and application.

Raw and auxiliary materials including chicken embryos, cell substrates, serum and adjuvants must pass sterility test, exogenous virus detection and mycoplasma examination before use, and unqualified materials are prohibited from application. Production water shall meet purified water standards, and disinfectants shall be replaced regularly with efficacy verification.

Standardized SOPs shall be strictly followed throughout the preparation process. For inactivated vaccines, the concentration, temperature and duration of inactivants shall be precisely controlled, followed by inactivation verification to ensure no residual live virus.

Procedures including lysis, purification, liquid preparation and subpackaging shall be conducted in Grade 10,000 clean areas with partial Grade 100 local environment, with real-time online monitoring of temperature, pH value and sterility status. Each vaccine batch shall undergo sterility test, abnormal toxicity test, potency test and safety test before entering the next production link.

Personnel management shall adopt access permission and daily health monitoring. Operators must receive professional biosafety training, wear sterile protective clothing, masks, goggles and double-layer gloves, and strictly follow standardized dressing and disinfection procedures. Daily health status screening is mandatory; staff with fever or respiratory symptoms shall be immediately suspended from post to prevent anthropogenic contamination and reverse viral transmission (see Table 1).

Table 1 Overview of Health Management Strategies

Management Dimension	Core Strategy	Implementation Method
Strain Screening	Precise matching and strong immunogenicity	Monitor prevailing epidemic strains; select strains with high matching degree, safety and high efficiency.
Production Environment	Biosafety assurance and sterile controllability	Implement GMP zoning and physical isolation; adopt negative pressure ventilation and one-way flow of personnel and materials.
Raw Material Control	Full-chain traceability and qualified access	Adopt double-person and double-lock management; all materials must pass qualification testing; apply purified water and regularly replace disinfectants with efficacy verification.
Preparation Process	Standard compliance and whole-process monitoring	Conduct strict inactivation verification; perform operations in clean areas; implement multi-batch quality inspection.
Personnel Management	Access authorization training and daily health monitoring	Post engagement with professional certification; standard sterile protection; daily health screening.

This link guarantees the safety and efficacy of vaccines through source quality control and biosafety safeguards, laying a solid foundation for subsequent procedures.

4.2 Health Management of Vaccine Cold Chain Storage and Transportation

Vaccine demands among occupationally exposed populations are relatively scattered, and the health management of storage and transportation involves numerous detailed standardized requirements in cold chain logistics. Based on the practical characteristics of cold chain storage and transportation, standardized health management is essential to fundamentally ensure the hygienic quality of vaccines before use and achieve optimal application effects.

The cold chain storage and transportation link establishes an uninterrupted health control system centered on whole-process temperature control, airtight cleanliness, traceability, and leakage and pollution prevention. Facilities and equipment are dedicated and standardized. Vaccines are stored in medical refrigerators at 2–8°C and are prohibited from being placed together with food, common drugs or sundries. Refrigerators are equipped with real-time temperature monitoring and over-limit alarm devices and are cleaned and disinfected regularly. Special refrigerated vehicles, incubators and ice packs are adopted for transportation. Containers must be pre-cooled to the specified temperature before packing to maintain a constant temperature of 2 – 8° C throughout transportation. Freezing, high-temperature exposure under direct sunlight, and long-term open placement are strictly forbidden.

Packaging and loading follow airtight and clean standards. Vaccine outer packages shall remain intact with clear labels, and surface disinfection shall be performed before transportation. Partition boards are placed inside incubators to avoid collision and breakage of vaccine vials; leaked vaccines shall be separately sealed and disposed of. Before loading, transport vehicles and containers are thoroughly cleaned, disinfected and ventilated to remove dirt and residual disinfectants and prevent contamination of vaccine vials.

Uninterrupted whole-process temperature monitoring and record-keeping are implemented with portable temperature recorders that automatically log temperature at fixed intervals. Data are exported and archived after transportation and retained for at least two years beyond the vaccine expiry date. The frequency of temperature monitoring is increased for long-distance transportation or high-temperature environments, and emergency plans are formulated. Once refrigeration failure or temperature deviation occurs, emergency cooling, isolation inspection and potency evaluation shall be initiated immediately, and unqualified vaccines shall be centrally destroyed.

Handover and acceptance adopt double-person verification and closed-loop management. Recipients shall strictly check the vaccine name, manufacturer, batch number, validity period, quantity, batch release certificate and transportation temperature records before signing for acceptance. Any vaccines with damage, leakage, contamination, expiry or abnormal temperature shall be immediately isolated and sealed, disposed of in accordance with medical waste regulations, and strictly prohibited from entering the vaccination process[6].

Through whole-process cold chain and cleanliness control, this procedure avoids vaccine potency decline, contamination and deterioration, and ensures that vaccines remain safe and effective upon arrival at vaccination sites.

4.3 Health Management of On-site Vaccination

The standardized management of on-site vaccination plays a vital role in achieving comprehensive control outcomes. On-site vaccination hygiene not only ensures the smooth progress of vaccination procedures but also underpins the construction of on-site biosafety barriers after vaccination.

Vaccination venues implement functional zoning and environmental control, including waiting area, registration area, vaccination area, observation area, first-aid area and temporary medical waste storage area, with physical isolation and adequate ventilation among all zones. Before vaccination, floors, tables, doors, windows and equipment surfaces are wiped and disinfected with chlorine-containing disinfectants or quaternary ammonium compounds; indoor air is purified by ultraviolet radiation or air disinfection machines. High-frequency contact surfaces are disinfected more frequently to avoid residual viral contamination in the environment.

Full coverage of personnel protection and health screening is enforced. Vaccination medical staff wear work uniforms, masks, gloves and caps; gloves are replaced or hand disinfection is performed after each vaccination. Wearing ornaments and long fingernails are prohibited. Vaccinees receive health inquiries and temperature screening, focusing on fever, acute respiratory infection, allergy history and immunodeficiency conditions. Contraindicated populations are excluded from vaccination, and cautious populations are deferred. Detailed occupational information of occupationally exposed groups is recorded to establish special archives, with priority given to vaccination for high-risk individuals.

Vaccination operations follow standardized aseptic procedures. The appearance of vaccines is visually inspected before use, and information is verified after shaking evenly. Aseptic instruments are used for opening vials to avoid contamination by rubber stopper debris during aspiration. The injection site is disinfected with 75% ethanol and allowed to dry before injection to prevent local infection. Disposable syringes are adopted following the principle of one person, one needle, one syringe, one use and one disposal, and reuse is strictly prohibited (see Figure 1).

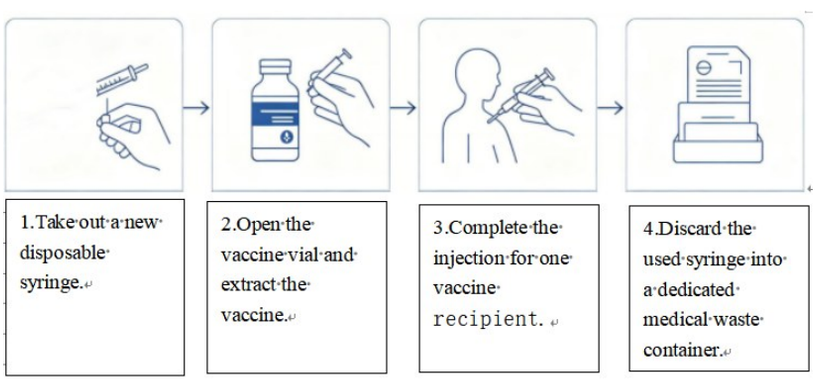


Figure 1

The opened vaccine should be used within the specified time, and any remaining vaccine shall be disposed of as medical waste. Closed-loop management is implemented for post-vaccination observation and emergency disposal. Vaccinees are required to stay for 30 minutes of medical observation after inoculation. First-aid medicines and equipment such as epinephrine and glucocorticoids shall be equipped with dedicated personnel on duty. Any adverse reactions such as allergy and syncope shall be treated in a standardized manner and reported immediately. At the end of daily vaccination work, terminal disinfection shall be comprehensively carried out at the site. Medical waste shall be collected by classification, double-layer sealed with clear labels, temporarily stored in dedicated containers, and centrally disposed of by qualified institutions.

This procedure directly targets high-risk groups. Through strict aseptic operation and on-site regulation, it blocks the risks of vaccine contamination, cross-infection and adverse reactions.

4.4 Health Management of Vaccine Waste and Subsequent Disposal

In view of the high risks of recombinant strain environmental contamination, waste transmission and illegal backflow caused by non-standard disposal, the waste disposal procedure adopts classified collection, airtight transportation, harmless treatment and whole-process supervision as the core principles to establish a full-process closed-loop management system.

Waste materials shall be precisely classified. Expired, damaged, contaminated and residual vaccines, together with empty vaccine vials, are categorized as infectious medical waste. Used syringes, cotton swabs, absorbent cotton and disinfection supplies are classified as injurious or infectious waste. Cold chain packaging materials and cleaning supplies are regarded as general contaminated waste. All categories shall be placed into designated containers separately, and mixed storage, leakage and random discarding are strictly prohibited.

Collection and packaging follow airtight and standardized requirements. Medical waste shall be packed in yellow dedicated medical waste bags and puncture-proof sharps containers. Once the container is filled to three-quarters capacity, the opening shall be tightly sealed and labeled with waste category, generating institution and date. All containers must be covered tightly for leakage and damage prevention. The outer surface shall be disinfected before transportation to avoid environmental and personnel contamination.

Transportation and handover adopt dedicated personnel and fixed routes under closed-loop delivery. Special vehicles operated by medically qualified disposal institutions are employed. Double-person verification and signed handover are mandatory, with complete transportation records detailing time, category, quantity and destination to ensure full traceability. Transportation routes shall avoid densely populated areas and drinking water sources to prevent leakage and spillover en route.

Harmless disposal shall be conducted in a standardized and thorough manner. Vaccine-related waste is prioritized for high-temperature high-pressure steam sterilization or incineration to ensure complete viral inactivation; random dumping, landfilling and abandonment are strictly forbidden. Empty vials and sharps shall be sterilized or crushed before resource recycling, so as to prevent secondary pollution caused by waste backflow into breeding and vaccination links.

This procedure closes the final loophole in vaccine management, strictly prevents environmental pollution, viral spread and waste reflux, and realizes a full-process closed-loop of hygienic safety.

5 Conclusion

In summary, pigs, as natural mixing vessels of influenza A viruses, can transmit diseases through multiple pathways, making standardized vaccine management particularly essential. It is critical to clarify management contents and key control points covering all links of vaccine lifecycle management.

Vaccination practitioners shall proceed from practical work, analyze the transmission mechanism of influenza A viruses, formulate targeted prevention and control measures, and ultimately achieve expected outcomes of vaccine health management. Reliable medical and health guarantees can effectively contain the spread of influenza A viruses.

References

[1] Han, D., Guo, X. J., Zhai, C. C., Deng, Y., Huang, B. Y., Hu, Y. C., Ren, J., Wang, W., Guo, J. J., Lu, F. N., Wang, W. L., Shen, X. L., Lu, Z. Z., Wang, J., & Tan, W. J. (2022). Bivalent recombinant adenovirus vector vaccine against SARS-CoV-2 Beta variant and influenza A H3N2 induces immune protection in mice. *Virologica Sinica*, *38*(5), 1025–1034.

[2] Ning, S., Ding, Y. H., Rong, H., Chi, Y., Ge, Y. Y., & Cui, L. B. (2025). Research path of vaccines and drugs for X disease: Enlightenment from COVID-19 and influenza A. *Jiangsu Journal of Preventive Medicine*, *36*(4), 408–414.

[3] Shao, Y. Q., Dong, W. B., Xia, Y. P., Zhang, C., & Liu, Y. (2025). Retrospective cohort study on protective effect of influenza vaccination against influenza A among population aged 3–17 years in Fenghua District, Ningbo, 2022–2023. *Shanghai Journal of Preventive Medicine*, *37*(8), 654–658.

[4] Shen, H. Q., Yu, K. Y., Chen, Y. Y., Ji, P., & Wang, Y. (2023). Preparation and boosting immunization strategy of mRNA vaccine based on hemagglutinin of influenza A H1N1 subtype. *Journal of Shanghai Jiao Tong University (Medical Science)*, *43*(11), 1374–1383.

[5] Wang, T. Q., Han, R. W., Cheng, X. T., Bing, J. L., Li, J., Sun, S. C., Guo, J. J., Zhai, C. C., Guo, X. Y., Wang, D. H., Wang, W. L., Zhou, J. F., Deng, Y., & Tan, W. J. (2024). Immune response and protection induced by hemagglutinin stem subunit vaccine of influenza A H1N1 combined with different adjuvants in mice. *Virologica Sinica*, *40*(1), 1–12.

[6] Zhou, Y. F., Yang, Z. H., Gao, J., Yuan, L., & Lei, H. (2025). Immunogenicity and protective efficacy of mRNA vaccine against influenza A (H1N1) in mice. *Chinese Pharmaceutical Journal*, *60*(10), 1013–1018.