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TRANSMISSION ROUTES AND ENVIRONMENTAL PERSISTENCE OF FOOT-AND-MOUTH DISEASE VIRUS (FMDV): AN OVERVIEW

RUTELE DE TRANSMITERE ȘI PERSISTENȚA ÎN MEDIU A VIRUSULUI FEBREI AFTOASE (FMDV): SINTEZĂ

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ABSTRACT

Foot-and-mouth disease virus (FMDV) is one of the most contagious animal pathogens, and it persists in diverse environmental matrices, being capable of spreading through multiple direct and indirect pathways. In this review, we synthesised the current evidence of transmission routes and the environmental persistence of FMDV. The major transmission pathways are represented by direct contact between infected and naïve animals, aerosol spread over long distances, and indirect exposure via contaminated fomites or environments. Feed, water, and milk are vehicles of infection, while improperly managed carcasses remain infectious for different periods. The soil, outdoor temperature, moisture, organic matter, and pH influence the environmental persistence of the virus, while survival of the pathogen is enhanced in cool weather, moist, and neutral conditions. The extreme pH, heat, and formaldehyde inactivate FMDV, although studies highlight its resilience under field conditions in soils, manure, and carcasses. In order to minimise outbreak risk, biosecurity measures, proper carcass disposal, and disinfection are needed. Therefore, it is essential to improve preparedness and inform control measures all over the world by understanding FMDV transmission dynamics and stability in the environment.

Keywords: Foot-and-mouth disease virus, transmission routes, environmental persistence

REZUMAT

Virusul febrei aftoase (FMDV) este unul dintre cei mai contagioși agenți patogeni la animale, persistă în diverse matrici din mediu și este capabil să se răspândească prin multiple căi directe și indirecte. În această sinteză sunt prezentate dovezile actuale referitoare la rutele de transmitere și persistența în mediu a FMDV. Principalele căi de transmitere sunt reprezentate de contactul direct între animale infectate și naive, răspândirea aerosolilor pe distanțe lungi și expunerea indirectă prin intermediul surselor secundare de infecție (fomite) sau al mediilor contaminate. Furajul, apa și laptele sunt vehicule ale infecției, în timp ce cadavrele gestionate necorespunzător rămân infecțioase pentru perioade diferite. Solul, temperatura exterioară,umiditatea, materia organică și pH-ul influențează persistența virusului în mediu, în timp ce supraviețuirea agentului patogen este sporită în condiții de temperatură reci, umiditate și condiții de pH neutre. Valori de pH extreme, căldura și formaldehida inactivează FMDV, deși studiile subliniază reziliența sa în condiții de teren în soluri, gunoi de grajd și cadavre. Pentru a minimiza riscul apariției unor focare de boală, sunt necesare măsuri de biosecuritate, eliminarea adecvată a cadavrelor și dezinfecția. Este esențial să se îmbunătățească pregătirea și să se deruleze campanii de informare privind măsurile de control la nivel global, dinamica transmiterii și stabilitatea FMDV în mediu.

Cuvinte cheie: Virusul febrei aftoase, rute de transmitere, persistența în mediu

Foot-and-mouth disease (FMD) is a highly contagious viral disease that affects cloven-hoofed animals, including cattle, pigs, sheep, goats, and wild ruminants (19, 20, 29). The disease is caused by the foot-and-mouth disease virus (FMDV), currently classified as the species *Aphthovirus vesiculae* in the genus *Aphthovirus*, subfamily *Caphthovirinae*, family *Picornaviridae*. This species includes seven immunologically distinct serotypes: FMDV-O, FMDV-A, FMDV-Asia1, FMDV-C, FMDV-SAT1, FMDV-SAT2, and FMDV-SAT3 (14). FMD is one of the most important transboundary animal diseases due to its rapid spread and substantial economic consequences. Although the disease has been controlled or eradicated in many high- and middle-income countries (recognised by WOAH as "disease-free territories" with or without vaccination), it is still estimated to threaten approximately 77% of the global livestock population (11, 25, 28). The socio-economic impact is deep, leading to large production losses, important trade restrictions, and huge costly eradication programmes (7). The transmissibility of the virus is attributed to its ability to spread through different routes, and it persists in different environments. Multiple epidemiological determinants act in concert to facilitate FMDV transmission, underscoring the complexity of the mechanisms governing viral introduction, dissemination and persistence in endemic settings (22). FMD is characterised by the formation of vesicles on the tongue, hard palate, dental pad,

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lips, gums, muzzle, coronary band and in the interdigital space. These lesions are accompanied by profuse salivation, anorexia, depression and lameness. The resulting pain and discomfort lead to reduced feed intake, impaired mobility and increased susceptibility to secondary infections at lesion sites. Overall, the clinical and pathological changes translate into marked reductions in productive and reproductive performance in affected livestock (5,10,11,16). This overview summarised findings from research experimental studies, epidemiological analyses, and modelling approaches in order to examine the main routes of transmission and the factors that influence FMDV persistence in the environment, with emphasis on their implications for outbreak management and biosecurity measures.

TRANSMISSION ROUTES OF FMDV

Direct Animal-to-Animal Contact

The most significant pathway for FMDV spread is direct contact. The virus is shad by infected animals through saliva, nasal secretions, vesicular fluids, urine, faeces, and milk. Persistently infected cattle, or so-called "carrier", harbour the virus in their oropharynx beyond the acute phase of infection. Arzt et al. (2018) demonstrated that oropharyngeal fluid from carrier cattle transmits FMDV to susceptible naïve animals, emphasising the epidemiological value of carrier animals without clinical signs in endemic situations (1).

Airborne Transmission

Airborne spread has over time played a critical role in major FMD outbreaks. Compared to ruminants, pigs are especially efficient aerosol producers because they contain FMDV that can travel several kilometres under favourable meteorological conditions (4). The viral load, wind direction, humidity, and temperature influence the distance of viral spread. Modelling and retrospective analyses highlight that the major outbreaks in Europe during the 20th century were amplified by airborne transmission across farms and even between countries.

Indirect Transmission via Contaminated Environments (Fomites)

Contaminated objects such as vehicles, equipment, clothing, and housing facilitate FMDV transmission. The risk of infection from environmental contamination in cattle was quantified, and it was demonstrated that virus deposited on surfaces retained sufficient infectivity to establish a new infection.The previous findings stress the importance of hygiene levels in farms and movement restrictions during outbreaks (9).

Feed- and Food-Borne Transmission

The infection of swine by feed is a well-documented risk pathway. Experimental studies have demonstrated that pigs can contract an infection by consuming contaminated feed (23). Jones et al. (2020) underscored the wider risk of feed serving as a vehicle for livestock pathogen transmission (15). In addition to feed, dairy products represent a major concern for trade. It has been reported that FMDV survives in raw and pasteurised milk, which points to the potential for dissemination of the virus through dairy chains (27).

Waterborne Transmission

The water can act as a vehicle for FMDV transmission, although it was less frequently documented in outbreaks. A quantitative risk assessment conducted by Schijven et al.(2005) suggested that contaminated water could pose risks under certain circumstances (21). The stability of FMDV in wet environments depends on temperature and pH, so that cold neutral pH water prolongs viral viability.

Carcass and Animal By-Product Transmission

Infected carcasses serve as reservoirs of virus viability. Pig carcasses remained infectious for several days, creating a risk if they are not properly disposed of (24). The carcass management practices are therefore critical: Guan et al. (2010) showed the inactivation of FMDV in infected pig carcasses by composting (12), while other studies emphasised the challenges of disposal on small- and medium-scale farms (8, 18).

Human-Mediated Transmission and Public Access

The spread of the virus can be inadvertently facilitated by human activity. The indirect human-mediated transmission (via clothing, footwear, or contact with livestock) may be underestimated in contingency planning, according to Auty et al. (2019), who evaluated the risk posed by public access to the countryside during outbreaks (2).

Table 1

Evidence of transmission routes of FMDV

Transmission Route	Key Findings	References
Direct contact	Oropharyngeal fluid from carriers can infect naïve cattle	Arzt et al. (2018)
Airborne	Pigs are efficient aerosol producers; spread can occur across km	Brown et al. (2022)
Indirect (environment)	Virus retained on contaminated surfaces can infect cattle	Colenutt et al. (2020)
Feed	Pigs susceptible via contaminated feed; broader feed-borne risks	Stenfeldt et al. (2021); Jones et al. (2020)
Milk/dairy	Virus survives in raw and pasteurized milk	Tomasula & Konstance (2004)
Water	Quantitative risk from contaminated sources	Schijven et al. (2005)

ENVIRONMENTAL PERSISTENCE OF FMDV

Survival in Soil

The survival of FMDV in soil is influenced by physical and chemical properties. Bessler et al. (2024) assessed virus persistence across U.S. soil types under high ambient temperatures, finding that shaded and moist soils preserved infectivity longer than dry, sun-exposed soils (3). As a conclusion, environmental heterogeneity directly impacts persistence during outbreaks.

Organic Material and Manure

Manure, bedding, and organic waste protect viable FMDV for a large period of time, contributing to environmental contamination. The importance of such reservoirs in endemic regions, where manure is often used as fertiliser or discarded without inactivation, has been emphasised by certain authors (17).

pH Sensitivity

FMDV is stable at neutral pH, but it is rapidly inactivated under acidic (<6.0) or alkaline (>9.0) conditions. Caridi et al. (2015) and Yuan et al. (2017) investigated structural determinants of pH stability, linking viral capsid residues to resistance or susceptibility to inactivation (6, 30). This knowledge is very useful to design inactivation protocols using acidic or alkaline treatments and substances. The formaldehyde treatment effectively inactivated local FMDV isolates, highlighting its role in disinfection (26).

Temperature and Thermal Inactivation

Heat was demonstrated as a method for viral inactivation. Gubbins et al. (2016) studied thermal inactivation in extruded pet food, and he confirmed that sufficient heat treatment eliminates FMDV infectivity (13). Environmental temperature also influences the persistence; on one hand, high temperatures accelerate inactivation, and on the other hand, cooler climates prolong viability.

Carcasses and Composting

Virus persistence in animal carcasses represents a critical challenge for biosecurity. Guan et al. (2010) demonstrated that composting facilitates viral degradation, making it a safe disposal strategy when it is properly managed compared to burial or inadequate composting, which may prolong environmental persistence (12).

INTEGRATED PERSPECTIVE OF TRANSMISSION AND PERSISTENCE

The outbreak dynamics is determined by transmission routes and environmental persistence. Virus shed by infected animals contaminate soil, water, feed, or fomites, translated in indirect exposure risk. The persistence in carcasses and in organic waste highlights the connection between animal health management and environmental biosecurity strategies. Airborne transmission presents a significant challenge because it can bypass conventional containment barriers. Put together, these pathways highlight the importance of multi-layered control plans.

IMPLICATIONS FOR CONTROL AND MITIGATION

Effective outbreak management requires interventions targeting both direct transmission and environmental persistence:

- Movement restrictions reduce direct and airborne spread.
- Enhanced farm biosecurity limits indirect and fomite-mediated risks.
- Carcass disposal protocols (composting, incineration, rendering) minimize persistence in dead animals.
- Water and soil management reduce environmental reservoirs, particularly in endemic regions.
- Feed biosecurity is critical for swine production systems.
- Disinfection protocols using heat, pH treatments, or formaldehyde enhance viral inactivation.

CONCLUSIONS

FMDV spreads by multiple interconnected routes similar to a network, such as direct contact, airborne particles, contaminated environments,feed,water, and carcasses. The virus demonstrates remanence in soils, manure, organic materials,and carcasses, with persistence that varies according to temperature, pH, and weather

Table 2

Environmental persistence of FMDV under different conditions

Environment	Persistence Findings	References
Soil	Survival varies by soil type, temperature, and moisture	Bessler et al. (2024)
Manure/organic waste	Prolonged survival in endemic regions	Mielke & Garabed (2019)
pH conditions	Inactivation at acidic (<6) and alkaline (>9) pH	Caridi et al. (2015); Yuan et al. (2017)
Heat	Extrusion/inactivation in the feed is confirmed	Gubbins et al. (2016)
Carcasses	Infectious virus found in carcasses; composting effective	Guan et al. (2010); Stenfeldt et al. (2020)
Milk	Virus survives in raw/pasteurized milk	Tomasula & Konstance (2004)
Water	Persistence possible; transmission risk via drinking water	Schijven et al. (2005)

conditions. Even if effective inactivation methods exist – such as heat, pH manipulation, and composting – the environmental survival of FMDV necessitates strict biosecurity and very fast response measures. Continued research in virus-environment interactions and transmission will be very important to improve outbreak preparedness, refine control strategies, and finally protect global livestock industries.

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