FOOT-AND-MOUTH DISEASE STANDARD OPERATING PROCEDURES: 1. OVERVIEW OF ETIOLOGY AND ECOLOGY

FAD PReP
Foreign Animal Disease Preparedness & Response Plan

United States Department of Agriculture

United States Department of Agriculture • Animal and Plant Health Inspection Service • Veterinary Services

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The Foreign Animal Disease Preparedness and Response Plan (FAD PReP) Standard Operating Procedures (SOP) provide operational guidance for responding to an animal health emergency in the United States.

These draft SOPs are under ongoing review. This document was last updated in **October 2020**. Please send questions or comments to:

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Foot-and-Mouth Disease

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Disease

Foot-and-mouth disease (FMD), fiebre aftosa, fievre aphteuse, maulund-klauenseuche.

Mortality & Morbidity

Very high morbidity; high mortality in young animals.

Susceptible Species

Domestic cloven hoofed animals (cattle, swine, sheep, goats) and wildlife (deer, bison, pronghorn antelope, feral swine).

Zoonotic Potential?

Not a threat to public health.

Carriers

Ruminants may become carriers of FMD; an estimated 50 percent of cattle may become carriers.

Transmission

Pigs excrete large amounts of virus through respiration. Virus spreads readily on contaminated equipment and other fomites. Windborne transmission can occur.

Persistence in the Environment

Survives longer at cold temperatures. Susceptible to acid and alkaline pH. Can remain infective for long periods of time where organic matter is present.

Animal Products and By-Products

FMD virus can survive for months in chilled/frozen bone marrow, lymph nodes, and can survive in sausages and other cured meats. Typical pasteurization may not completely inactivate FMD from milk.

1.1 Introduction

Foot-and-mouth disease (FMD) is a highly contagious viral disease that affects domestic cloven-hoofed animals (cattle, swine, sheep, and goats) and more than 70 wildlife species (deer, bison, pronghorn antelope, and feral swine). The disease is characterized by fever, vesicular (blister-like) lesions, and subsequent erosions on the surfaces of the mouth, tongue, nostrils, muzzle, feet, and teats.

FMD is one of the most contagious livestock diseases and endemic in many areas of the world; introduction of FMD into the United States is a serious concern. All secretions, excretions, and tissues are contagious, and the virus may be present in respirations, milk, and semen. The virus enters a new susceptible animal either orally (especially swine) or via the respiratory tract (especially cattle). Aerosol transmission is the major means of animal-to-animal spread within premises. Though FMD virus (FMDV) is not typically considered a zoonotic disease, and is not a threat to public health, there is evidence demonstrating humans can carry the virus mechanically in their nasal passages.[1,2,3]

FMD is not normally characterized by high death rates in adult animals, but it can produce morbidity rates of almost 100 percent, resulting in severe losses to productivity. It is probable that all animals in a susceptible population will be affected. Although it does not tend to kill adults, high mortality rates may be observed in young animals.[4,5,6]

1.1.1 Goals

As a preparedness goal, the Animal and Plant Health Inspection Service (APHIS) will provide etiology and ecology summaries for FMD, and update these summaries at regular intervals.

As a response goal, the Unified Command and stakeholders will have a common set of etiology and ecology definitions and descriptions, to ensure proper understanding of FMD when establishing or revising goals, objectives, strategies, and procedures.

1.1.2 Further Information

This document is intended to be an overview, focusing on FMD in domestic livestock. Additional resources on FMD are listed in Attachment 1.A. The *FMD Response Plan: The Red Book* provides case definitions and laboratory criteria from the APHIS Center for Epidemiology and Animal

[1] Sellers, R.F., et al. (1970). Inhalation, persistence and dispersal of foot-and-mouth disease virus by man. *Journal of Hygiene* (London), *68*(4), 565–573. DOI: 10.1017/s0022172400042492.
[2] Amass, S., et al. (2003). Procedures for preventing the transmission of foot-and-mouth disease virus to pigs and sheep by personnel in contact with infected pigs. *Veterinary Record*, *153*(5), 137–140. DOI: 10.1136/vr.153.5.137.
[3] Amass, S., Pacheco, J., Mason, P., Pacheco, J., Miller, C., Ramirez, A., Clark, L., Ragland, D., Schneider, J., & Kenyon, S. (2004). Procedures for preventing transmission of foot-and-mouth disease virus (O/TAW/97) by people. *Veterinary Microbiology*, *103*(3–4), 143–149. DOI: 10.1016/j.vetmic.2004.07.020.
[4] Musser, J.M. (2004). A practitioner's primer on foot-and-mouth disease. *Journal of the American Veterinary Medical Association*, *224*(8), 1261–1268. DOI: 10.2460/javma.2004.224.1261.
[5] Kitching, R.P. & Alexandersen, S. (2002). Clinical variation in foot and mouth disease: pigs. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 513–518. DOI: 10.20506/rst.21.3.1367.
[6] Kitching, R.P. & Hughes, G.J. (2002). Clinical variation in foot and mouth disease: sheep and goats. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 505–512. DOI: 10.20506/rst.21.3.1342.

Health.

This document does not comprehensively discuss vaccination, or its effects on immunity. For more specific technical information related to vaccination, as well as a detailed review of scientific literature relating to FMD, and please see the *National Animal Health Emergency Management System (NAHEMS) Guidelines: Vaccination for Contagious Diseases, Appendix A: FMD*.

These documents are available on the APHIS Foreign Animal Disease Preparedness and Response (FAD PReP) website: www.aphis.usda.gov/fadprep.

1.2 Purpose

This document provides responders and stakeholders with a common understanding of the disease agent.

1.3 Etiology

1.3.1 Name

This disease is called foot-and-mouth disease, fiebre aftosa, fievre aphteuse, and maulund-klauenseuche.

1.3.2 Virus Characteristics

According to the International Committee on Taxonomy of Viruses, this disease has the following characteristics:[7]

- Family: Picornaviridae
  - Genus: *Aphthovirus*, containing four species:
    - Foot-and-mouth disease virus
    - Bovine rhinitis A virus
    - Bovine rhinitis B virus
    - Equine rhinitis A virus
- Baltimore Classification: Group IV (+) ssRNA.[8,9]

[7] International Committee on Taxonomy of Viruses. (2019). Foot-and-Mouth Disease. Retrieved from https://talk.ictvonline.org/ictv-reports/ictv_online_report/positive-sense-rna-viruses/picornavirales/w/picornaviridae/707/genus-aphthovirus.
[8] Adams, R.L.P., et al. (1992). The structure of viruses. *The biochemistry of the nucleic acids* (p. 75–76). United Kingdom: Chapman & Hall. DOI: 10.1007/978-94-011-2290-0.
[9] Shors, T. (2013). Baltimore classification. In *Understanding viruses* (56). Burlington, MA: Jones & Bartlett Learning.

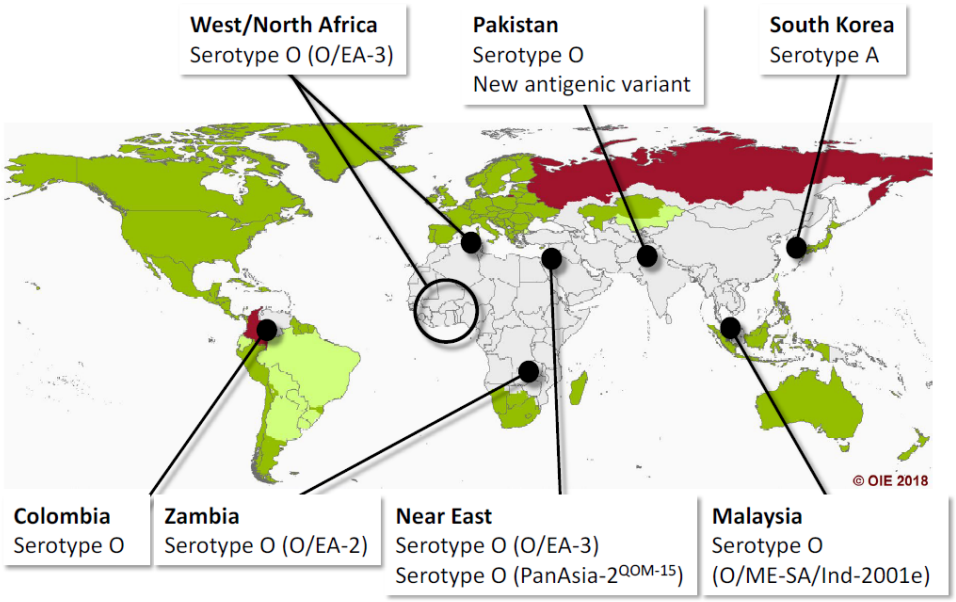
1.3.3 Morphology

FMD is a single-stranded ribonucleic acid (RNA) virus, approximately 30 nanometers in diameter, with icosahedral symmetry. There are 60 copies of four structural proteins, VP1, VP2, VP3, and VP4. These proteins encapsidate a single strand of positive-sense RNA[10,11,12]

1.3.4 FMD Serotypes and Strains

There are seven serotypes of FMD: O, A, C, Asia-1, and South African Territories (SAT) 1, SAT 2, and SAT 3. Type O is the most prevalent serotype worldwide, followed by type A.[13] Within these serotypes, more than 60 strains have been identified.[14] Figure 1-1 illustrates the typical distribution of serotypes in recent outbreaks.[15,]

Figure 1-1. Worldwide FMD Events in 2018



Source: OIE Foot-and-Mouth Disease Reference Laboratory Network 2018 Annual Report.

[10] Belsham, G. & Bøtner, A. (2015). Use of recombinant capsid proteins in the development of a vaccine against foot-and-mouth disease virus (FMDV). *Virus Adaptation and Treatment*, *7*, 11–23. DOI: 10.2147/VAAT.S55351.
[11] Gay, C.G., et al. (2010). Foot-and-Mouth Disease (FMD): Gap Analysis Workshop Report. In *Agricultural Research Service*. Retrieved from http://go.usa.gov/kCqF.
[12] Goodwin, S., et al. (2009). Foot-and-mouth disease virus assembly: processing of recombinant capsid precursor by exogenous protease induces self-assembly of pentamers in vitro in a myristoylation-dependent manner. *Journal of Virology*, *83*(21), 11275–11282. DOI: 10.1128/JVI.01263-09.
[13] Gay, C.G., et al. (2010). Foot-and-Mouth Disease (FMD): Gap Analysis Workshop Report. In *Agricultural Research Service*. Retrieved from http://go.usa.gov/kCqF.
[14] Center for Food Security and Public Health (CFSPH). (2014). Foot-and-Mouth Disease. In *Technical Factsheet.* Retrieved from www.cfsph.iastate.edu.
[15] World Organization for Animal Health (OIE)/Food and Agriculture Organization (FAO) Foot-and-Mouth Disease Reference Laboratory Network. (2018). Annual Report. Retrieved from: https://www.foot-and-mouth.org/sites/foot/files/user-files/research-paper/pdf/11-19/OIE-FAO%20FMD%20Ref%20Lab%20Network%20Report%202018.pdf..

FMDV is highly susceptible to change, resulting from errors in RNA replication, recombination, and host selection.[16] There is no cross-protection between the distinct serotypes.[17] Protection within serotypes varies based on the antigenic similarity of the strains. Subsequently, any vaccine must be carefully matched with the field strain to be effective. For more information on FMD vaccination matching, please see the *FAD PReP/NAHEMS Guidelines: Vaccination for Contagious Diseases*, *Appendix A: FMD* found at www.aphis.usda.gov/fadprep.

1.4 Ecology

1.4.1 General Overview

FMD is currently endemic in areas of Africa, Asia, Eastern Europe, the Middle East, and South America.[18] Seven of these countries maintain FMD OIE-endorsed control programs: China, India, Kyrgyzstan, Mongolia, Morocco, Namibia, and Thailand.[19] Only 68 countries, including those of North America (the United States, Canada, and Mexico), Central America, and Western Europe, as well as Australia and New Zealand are free of FMD (without vaccination).[19,20] The last FMD outbreak in the United States was in 1929.[21]

1.4.2 Susceptible Species

FMDV infects cloven-hooved mammals (order *Artiodactyla*), as well as a few species in other orders. Livestock susceptible to FMD, common in the United States, include:

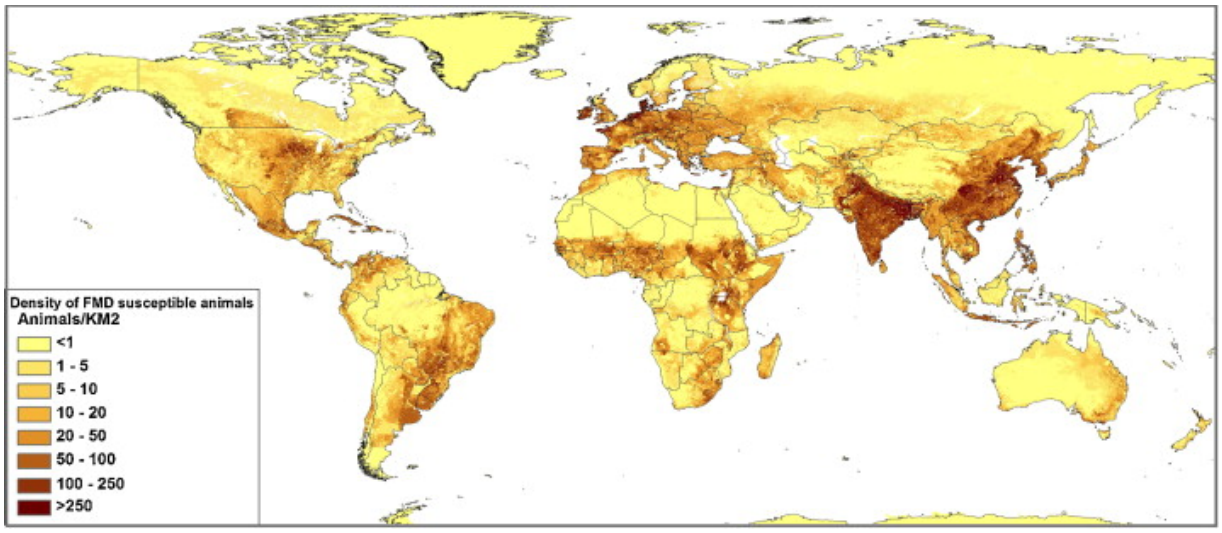
- cattle,
- pigs,
- sheep, and
- goats.

In addition, deer, bison, and elk are also susceptible to the virus. Wild pigs, antelope, African buffalo, Bactrian camels, elephants and giraffe are also all susceptible species. Llamas and alpacas have been infected experimentally, but do not seem to be highly susceptible to natural infection. Other animals like rats, mice, guinea pigs, and armadillos have all been experimentally infected.[22,23,24] Strains may have a predilection for one animal species over another.[25] For

[16] OIE. (2013). Foot and Mouth Disease. In *Technical Disease Card*. Retrieved from http://www.oie.int.
[17] OIE. (2013). Foot and Mouth Disease. In *Technical Disease Card*. Retrieved from http://www.oie.int.
[18] OIE. (2013). Foot and Mouth Disease. In *Technical Disease Card*. Retrieved from http://www.oie.int.
[19] OIE. (2020). Foot-and-Mouth Disease. *List of Members with endorsed official control programme for FMD*. Retrieved from https://www.oie.int/animal-health-in-the-world/official-disease-status/fmd/fmd-official-control-programme/.
[20] For a list of the regions considered to be free of Foot-and-Mouth Disease by U.S. Department of Agriculture (USDA) APHIS, please see https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/animal-and-animal-product-import-information/animal-health-status-of-regions.
[21] CFSPH. (2014). Foot-and-Mouth Disease. In *Technical Factsheet.* Retrieved from www.cfsph.iastate.edu.
[22] Musser, J.M. (2004). A practitioner's primer on foot-and-mouth disease. *Journal of the American Veterinary Medical Association*, *224*(8), 1261–1268. DOI: 10.2460/javma.2004.224.1261.
[23] OIE. (2013). Foot and Mouth Disease. In *Technical Disease Card*. Retrieved from http://www.oie.int.
[24] Lubroth, J., et al. (1990). Foot-and-mouth disease virus in the llama (*Lama glama*): diagnosis, transmission, and susceptibility. *Journal of Veterinary Diagnostic Investigation*, *2*(3), 197–203. DOI: 10.1177/104063879000200308.
[25] CFSPH. (2014). Foot-and-Mouth Disease. In *Technical Factsheet.* Retrieved from www.cfsph.iastate.edu.

example, serotype O, Cathay topotype, causes severe disease in pigs, but not in cattle.[26] Figure 1-2 presents the density of FMD susceptible livestock species in the world.

Figure 1-2. Density of FMD Susceptible Animals Livestock Species, i.e., Combined Cattle, Pigs, Sheep, and Goats



Source: Knight-Jones, T. and Rushton, J. (n.d.).

1.4.3 Carrier State

A carrier is defined as an animal in which there is persistence of FMDV or the viral genome in the pharyngeal region for at least 28 days post-infection.[27,28] Generally speaking, a "carrier" is defined in epidemiological terms as an animal that is infected and can disseminate the infection in the absence of symptoms. This is to be distinguished from animals with neoteric infections, or subclinical infections of hosts immune from fulminant disease, e.g., vaccinated animals.

Animals with neoteric infections may shed large amounts of virus; however, with FMD, carrier animals shed low amounts of virus[26,29] and may or may not be able to transmit infection in field conditions.[28] African buffalo are the only carrier animals that have been demonstrated to be able to

[26] Stenfeldt, C. & Arzt, J. (2020). The Carrier Conundrum; A Review of Recent Advances and Persistent Gaps Regarding the Carrier State of Foot-and-Mouth Disease Virus. *Pathogens 2020, 9*(3), 167. Retrieved from https://doi.org/10.3390/pathogens9030167.

[27] Sutmoller, P., et al. (1968). The epizootiological importance of foot-and-mouth disease carriers. I: Experimentally produced foot-and-mouth disease carriers in susceptible and immune carriers. *Archives of Virology*, *23*(3), 227–235. DOI: 10.1007/BF01241895.

[28] Sutmoller, P. & Casas-Olascoaga, R. (2002). Unapparent foot and mouth disease infection (sub-clinical infections and carriers): implications for control. *Scientific and Technical Review of the Office International des Epizooties, 21*(3), 519–529. DOI: 10.20506/rst.21.3.1366.

[29] Alexandersen, S., et al. (2002). Aspects of the persistence of foot-and-mouth disease virus in animals—the carrier problem. *Microbes and Infection*, *4*(10), 1099–1110. DOI: 10.1016/S1286-4579(02)01634-9. Retrieved from https://www.sciencedirect.com/science/article/pii/S1286457902016349.

definitively transmit FMDV (SAT serotypes) to other buffalo and potentially cattle.[30,31,32,33] For more information on carrier transmission, please see the *FAD PReP/NAHEMS Guidelines: Vaccination for Contagious Diseases*, *Appendix A: FMD* found at www.aphis.usda.gov/fadprep.

In addition to African buffalo, water buffalo, cattle, sheep, and goats can also become carriers. The duration of the carrier state in farm animals has been reported to be as long as 3.5 years for cattle and 9 months for small ruminants.[34] Commonly, studies indicate that greater than 50% of infected cattle may still harbor FMD virus 6 weeks to 6 months after initial infection, clearing within 2 years.[26,35,36] Persistent infections have also been identified in some experimentally infected wildlife species, including white-tailed deer and kudu, but not feral swine.[37]

There has been no carrier state identified in swine.[26,38] Pigs clear FMDV from sera, oral, nasal or oropharyngeal fluids in 28 days, although FMDV RNA could be extracted from lymph node tissue at 60 days post-infection.[39]

The epidemiological significance of carrier animals in FMD outbreaks of cattle is uncertain. Although there is no evidence that any carrier species can transmit FMDV in the field to naïve animals, the perception of risk remains and cannot be discounted. The prevalence of carrier animals in a herd and factors influencing this prevalence—regardless of whether vaccination is

[30] Alexandersen, S., et al. (2002). Aspects of the persistence of foot-and-mouth disease virus in animals—the carrier problem. *Microbes and Infection*, *4*(10), 1099–1110. DOI: 10.1016/S1286-4579(02)01634-9.
[31] Sutmoller, P. & Casas-Olascoaga, R. (2002). Unapparent foot and mouth disease infection (sub-clinical infections and carriers): implications for control. *Scientific and Technical Review of the Office International des Epizooties, 21*(3), 519–529. DOI: 10.20506/rst.21.3.1366.
[32] Condy, J.B., et al. (1985). The duration of the foot-and-mouth disease virus carrier state in African buffalo (i) in the individual animal and (ii) in a free-living herd. *Comparative Immunology, Microbiology & Infectious Diseases*, *8*(3–4), 259–265. DOI: 10.1016/0147-9571(85)90004-9.
[33] Anderson, E.C., et al. (1979). The pathogenesis of foot-and-mouth disease in the African buffalo (*Syncerus caffer*) and the role of this species in the epidemiology of the disease in Kenya. *Journal of Comparative Pathology*, *89*(4), 541–549. DOI: 10.1016/0021-9975(79)90045-8.
[34] Bronsvoort, B. M. d. et al. (2016). Redefining the "carrier" state for foot-and-mouth disease from the dynamics of virus persistence in endemically affected cattle populations. *Sci. Rep. 6,* 29059. DOI: 10.1038/srep29059. Retrieved from https://www.nature.com/articles/srep29059.
[35] Stenfeldt, C., Eschbaumer, M., Rekant, S.I., Pacheco, J.M., Smoliga, G.R., Hartwig, E.J.,Rodriguez, L.L., Arzt, J. (2016). The foot-and-mouth disease carrier state divergence in cattle. *J. Virol. 90*, 6344–6364. Retrived from https://jvi.asm.org/content/90/14/6344.
[36] Bertram, M. et al. (2020). Extinction dynamics of the foot-and-mouth disease virus carrier state under natural conditions. *Front. Vet. Sci., 20 May 2020.* Retrieved from https://doi.org/10.3389/fvets.2020.00276.
[37] Sutmoller, P. & Casas-Olascoaga, R. (2002). Unapparent foot and mouth disease infection (sub-clinical infections and carriers): implications for control. *Scientific and Technical Review of the Office International des Epizooties, 21*(3), 519–529. DOI: 10.20506/rst.21.3.1366.
[38] Kitching, R.P. (2002). Identification of foot and mouth disease virus carrier and subclinically infected animals and differentiation from vaccinated animals. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 531–538. DOI: 10.20506/rst.21.3.1365.
[39] Stenfeldt., C., et al. (2016). Detection of foot-and-mouth disease virus RNA and capsid protein in lymphoid tissues of convalescent pigs does not indicate existence of a carrier state. *Transbound Emerg Dis. 63*(2). DOI:10.1111/tbed.12235. Retrieved from https://onlinelibrary.wiley.com/doi/full/10.1111/tbed.12235.

employed—continues to require additional research.[40,41] The *NAHEMS Guidelines: Vaccination for Contagious Diseases, Appendix A: FMD* contains more information on the known epidemiological role and prevalence of carrier animals, impact of vaccination on carrier status, and detection of carriers via diagnostic testing.

1.4.4 Introduction and Transmission of FMDV

FMD is highly contagious. FMDV is typically introduced via contact with infected animals, their secretions, excretions, or fomites, or products contaminated with FMDV. FMD can also be introduced into a naïve animal population by feeding contaminated meat, milk, or garbage.[42,43] Conveyances may be responsible for transmitting the disease between an infected and an uninfected premises.[44] Insects and birds may also be mechanical vectors; no biological vector of the virus has been identified.[45]

Cattle typically become infected through aerosolized virus.[46] Pigs usually become infected by eating virus-contaminated food, or through direct contact with the vesicular lesions of other animals.[47,48] Pigs also can excrete large quantities of the virus through respiration, infecting susceptible animals.[49] As such, pigs are considered key amplifiers of the virus.[50]

1.4.4.1 Live Animals and Virus Shedding

Animal to animal contact is a common mode of transmission. FMDV is shed in all secretions and excretions, including saliva, milk, semen, and ruptured vesicular fluid, and to a lesser extent, feces and urine. Pigs produce nearly 3,000-fold more of FMDV in respiratory secretions than either

[40] Tenzin, et al. (2008). Rate of foot-and-mouth disease virus transmission by carriers quantified from experimental data. *Risk Analysis*, *28*(2), 303–309. DOI: 10.1111/j.1539-6924.2008.01020.x.
[41] Donaldson A.I. & Kitching, R.P. (1989). Transmission of foot-and-mouth disease by vaccinated cattle following natural challenge. *Research in Veterinary Science*, *46*(1), 9–14.
[42] Musser, J.M. (2004). A practitioner's primer on foot-and-mouth disease. *Journal of the American Veterinary Medical Association*, *224*(8), 1261–1268. DOI: 10.2460/javma.2004.224.1261.
[43] Donaldson, A.I. & Alexandersen, S. (2002). Predicting the spread of foot and mouth disease by airborne virus. *Scientific and Technical Review of the Office International des Epizooties (Paris)*, *21*(31), 569–575. DOI: 10.20506/rst.21.3.1362.
[44] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[45] Hugh-Jones, M.E. & Wright, P.B. (1970). Studies on the 1967–8 foot-and-mouth disease epidemic: The relation of weather to the spread of disease. *Journal of Hygiene*, *68*(2), 253–271. DOI: 10.1017/s0022172400028722.
[46] Kitching, R.P. & Hughes, G.J. (2002). Clinical variation in foot-and-mouth disease: cattle. *Scientific and Technical Review of the Office International des Epizooties*, 21(3), 499–504. DOI: 10.20506/rst.21.3.1343.
[47] Kitching, R.P. & Alexandersen, S. (2002). Clinical variation in foot and mouth disease: pigs. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 513–518. DOI: 10.20506/rst.21.3.1367.
[48] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[49] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[50] Amass, S., et al. (2003). Procedures for preventing the transmission of foot-and-mouth disease virus to pigs and sheep by personnel in contact with infected pigs. *Veterinary Record*, *153*(5), 137–140. DOI: 10.1136/vr.153.5.137.

cattle or sheep.[51,52] The amount of virus excreted by various species will also vary based on the serotype and strain of the FMDV.[53] Table 1-1 provides the approximate amount of virus excretion for cattle, pigs, and small ruminants, respectively in A, B, and C, indicating the significant difference in their levels of virus shedding.

Table 1-1. FMDV Excretion[54]

Table 1A
Descriptive statistics on data retrieved from the literature on maximum virus excretion from cattle.

FMDV infection variables	Number of observations	Maximum titre average (range) $TCID_{50}/ml^{*}$	Maximum titre standard deviation $TCID_{50}/ml^{*}$
Total	220	4.51 (0.95,8.65)	1.66
Type of secretion and excretion			
Airborne	9	4.33 (3.88, 5.08)	0.36
Blood	47	4.03 (0.95,6.20)	1.18
Faeces	5	1.55 (1.50, 1.75)	0.10
Milk	40	4.48 (2.15, 7.35)	1.46
URT (OPF swabs, saliva and nasal discharge)	33	5.70 (1.25, 8.50)	1.66
Nasal discharge only	7	6.09 (2.75, 7.85)	1.61
Probang	68	4.91 (2.20, 8.65)	1.53
Semen	8	4.55 (2.10, 6.20)	1.33
Urine	10	1.93 (1.00, 3.80)	0.87
Route of infection			
Intranasal	37	4.68 (0.95, 8.65)	1.76
Parenteral	95	4.75 (1.25, 8.50)	1.63
Contact	88	4.17 (1.00, 8.05)	1.57
Undetermined	1	4.60 (NA)	NA
FMDV serotype			
A	38	3.98 (2.10, 8.05)	1.40
O	140	4.54 (0.95, 8.65)	1.68
Asia-1	4	4.10 (2.80, 5.00)	0.80
C	6	4.6 (2.10, 7.00)	1.80
SAT (1, 2, 3)	12	4.26 (2.10, 6.00)	1.06

[51] Thomson, G. R. (1996). The role of carrier animals in the transmission of foot and mouth disease. In *OIE comprehensive reports on technical items presented to the International Committee or to Regional Commissions* (p. 87–103). Retrieved from http://www.oie.int/doc/ged/D3014.PDF.
[52] Donaldson, A.I. (1983). Quantitative data on airborne foot-and-mouth disease virus; its production, carriage, and deposition. *In Philosophical Transactions of the Royal Society of London, Series B, 302*(1111), 529–534. DOI: 10.1098/rstb.1983.0072.
[53] Donaldson, A.I., et al. (1970). Further investigations on the airborne excretion of foot-and-mouth disease virus. *Journal of Hygiene, 68*(4), 557–564. DOI: 10.1017/s0022172400042480.
[54] Bravo de Rueda, C., et al. (2014). Identification of factors associated with increased excretion of foot-and-mouth disease virus. *Prev. Vet. Med. 113*(1). DOI: 10.1016/j.prevetmed.2013.10.005. Retrived from https://doi.org/10.1016/j.prevetmed.2013.10.005.

Table 1-1. FMDV Excretion, cont'd[54]

Table 1B
Descriptive statistics on maximum virus excretion from swine.

FMDV infection variables	Number of observations	Maximum titre average (range) $TCID_{50}/ml^*$	Maximum titre standard deviation $TCID_{50}/ml^*$
Total	71	5.15 (3.41, 8.60)	0.98
Type of secretion and excretion			
Airborne	22	6.00 (4.48, 8.60)	0.89
Blood	6	5.18 (3.90, 6.50)	1.07
OPF (swabs and saliva)	43	4.70 (3.41, 6.45)	0.66
Route of infection			
Parenteral	39	5.44 (3.85, 8.08)	0.84
Contact	32	4.78 (3.41, 8.60)	1.01
FMDV serotype			
A	5	5.65 (4.48, 6.68)	0.70
O	64	5.01 (3.41, 6.54)	0.81
C	2	8.34 (8.08, 8.60)	0.26

Table 1C
Descriptive statistics on maximum virus excretion from small ruminants (sheep and goats).

FMDV infection variables	Number of observations average (range)	Maximum titre standard deviation $TCID_{50}/ml^*$	Maximum titre $TCID_{50}/ml^*$
Total	36	3.93 (0.86, 6.28)	1.25
Type of secretion and excretion			
Airborne	12	3.75 (2.38, 5.08)	1.00
Blood	8	3.34 (1.50, 5.20)	1.13
OPF (swabs and saliva)	16	4.37 (0.86, 6.28)	1.31
Route of infection			
Intranasal	11	4.69 (3.26, 6.28)	0.83
Parenteral	18	3.51 (1.50, 5.20)	1.10
Contact	6	3.70 (0.86, 5.45)	1.64
Undetermined	1	4.60 (NA)	NA
FMDV serotype			
A	2	2.53 (2.48, 2.58)	0.05
O	23	4.35 (0.86, 6.30)	1.12
C	3	3.28 (2.38, 5.08)	1.27

Total refers to all the maximum titres observations that were encountered.

* $TCID_{50}$ per animal per day for airborne excretion; dose of infection and days post infection were divided as above and below the median of the maximum titre calculated using the maximum titres when either the dose of infection or the days post infection were available.

Because cattle are more likely to be infected through inhalation, and pigs shed a significant amount of FMDV via respiration, highly concentrated herds of infected pigs in close proximity to naïve cattle herds poses a significant risk of transmission from pigs to cattle.[55]

1.4.4.2 Air/Windborne Transmission

Airborne FMDV can result from a large number of infected pigs, resulting in plumes of aerosolized virus in the atmosphere.[56] Cattle, because they inhale more air and are easily infected

[55] Donaldson, A.I. & Alexandersen, S. (2002). Predicting the spread of foot and mouth disease by airborne virus. *Scientific and Technical Review of the Office International des Epizooties (Paris)*, *21*(31), 569–575. DOI: 10.20506/rst.21.3.1362.

[56] Morris, R.S., et al. (2002). Decision-support tools for foot and mouth disease control. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 557–567.

through respiration, are the species frequently infected when FMDV is airborne.[57] Under specific climate conditions (particularly downwind), aerosolized FMDV produced by infected pigs can travel a significant distance often infecting cattle from upwards of 10 kilometers (km)—20-300 km being predicted with simulation models in the United Kingdom, and infecting sheep from 10–100 km away.[58,59]

Many different factors influence how well FMD aerosolizes, and how far aerosolized virus may spread. As already mentioned, the species of the infected animal is significant, as pigs excrete more virus through respiration than cattle or sheep. In addition, the amount of virus emitted into the air will be impacted by the stage of the disease in the infected animal, as well as the number and concentration of infected animals, and the strain of the virus.[60] In terms of climatic conditions, a relative humidity of 55 percent or more, with low and steady winds, is favorable for FMDV spread via aerosol.[61,62,63] The virus also seems to spread significantly better over water than over land.[64]

1.4.4.3 Fomite Transmission

FMDV is readily transmitted through vehicles, equipment, boots, clothing, and other fomites. In an FMD outbreak, the movement of fomites is a critical transmission pathway which must be addressed, particularly because FMDV can persist on fomites for an extended period of time with persistence based on many factors, including decreased temperatures.[65]

1.4.4.4 Personnel

One experimental study demonstrated that humans can harbor FMDV in their nasal passages for 28 hours (one subject), although the concentration of virus was markedly reduced over the first 3.5

[57] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[58] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[59] Donaldson, A.I. & Alexandersen, S. (2002). Predicting the spread of foot and mouth disease by airborne virus. *Scientific and Technical Review of the Office International des Epizooties (Paris)*, *21*(31), 569–575. DOI: 10.20506/rst.21.3.1362.
[60] Donaldson, A.I. & Alexandersen, S. (2002). Predicting the spread of foot and mouth disease by airborne virus. *Scientific and Technical Review of the Office International des Epizooties (Paris)*, *21*(31), 569–575. DOI: 10.20506/rst.21.3.1362.
[61] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[62] Donaldson, A.I. & Alexandersen, S. (2002). Predicting the spread of foot and mouth disease by airborne virus. *Scientific and Technical Review of the Office International des Epizooties (Paris)*, *21*(31), 569–575. DOI: 10.20506/rst.21.3.1362.
[63] Donaldson, A.I. (1972). The influence of relative humidity on the aerosol stability of different strains of foot and mouth disease virus suspended in saliva. *Journal of General Virology*, *15*(1), 25–33. DOI: 10.1099/0022-1317-15-1-25.
[64] Morris, R.S., et al. (2002). Decision-support tools for foot and mouth disease control. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 557–567.
[65] Cottral, G.E. (1969). Persistence of foot-and-mouth disease virus in animals, their products and the environment. *Scientific and Technical Review of the Office International des Epizooties*, *71*(3–4), 549–568.

hours post-exposure and below the assay limit of detection in 24 hours in the other subjects.[66] Under experimental conditions, personnel carrying the virus in this manner were able to transmit infection to naïve animals.[67] For this reason, responders may be advised by regulatory officials to employ a waiting period when traveling between premises. Evidence suggests that with appropriate biosecurity and cleaning and disinfection measures, the necessity for extended personnel waiting times or down periods is lessened.[68]

1.4.4.5 Wildlife

It is unclear what role wildlife would play in disease transmission if there was an FMD outbreak in the United States, Red, fallow, and roe deer were all susceptible to FMDV when exposed in the laboratory, though severity of clinical signs varied.[69] However, in the 2001 epidemic in the United Kingdom, evidence suggests deer were not epidemiologically important in the spread of FMD.[70,71] A general conclusion is that wildlife would not likely play a role in transmission of FMDV to livestock in a U.S. FMD outbreak, with acknowledgement that propagation of disease by wildlife should be a consideration in a response effort.[26,72,73]

1.4.5 Incubation Period

The incubation period for FMD is typically 2–14 days, and is defined by the World Organization for Animal Health (OIE) as 14 days for the purpose of the *OIE Terrestrial Animal Health Code* (2019).[74,75] During the beginning phases in the prevalence of FMDV, the incubation period may be as short as 24 hours.[76] How fast clinical signs appear depends on the dose of the virus, species of the animal, as well as the route of infection.[77,78] Animals may shed FMDV before the appearance

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[66] Sellers, R.F., et al. (1970). Inhalation, persistence and dispersal of foot-and-mouth disease virus by man. *Journal of Hygiene* (London), *68*(4), 565–573. DOI: 10.1017/s0022172400042492. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2130876/pdf/jhyg00094-0056.pdf.

[67] Sellers, R.F., et al. (1970). (1971). Transfer of foot-and-mouth disease virus in the nose of man from infected to non-infected animals. *Veterinary Record*, *89*(16), 447–449. DOI: 10.1136/vr.89.16.447-a.

[68] Amass, S., et al. (2003). Procedures for preventing the transmission of foot-and-mouth disease virus to pigs and sheep by personnel in contact with infected pigs. *Veterinary Record*, *153*(5), 137–140. DOI: 10.1136/vr.153.5.137. Retrieved from https://veterinaryrecord.bmj.com/content/vetrec/153/5/137.full.pdf.

[69] Forman, A.J. & Gibbs, E.P.J. (1974). Studies with foot-and-mouth disease virus in British deer (red, fallow, and roe): 1. Clinical Disease. *Journal of Comparative Pathology*, *84*(2), 215–220. DOI: 10.1016/0021-9975(74)90062-0.

[70] McVicar, J.W., et al. (1974). Foot-and-mouth disease in white tailed deer: clinical signs and transmission in the laboratory. In *Proceedings of the 78th annual meeting of the United States Animal Health Association* (p. 169–180).

[71] Davies, G. (2002). The foot and mouth disease epidemic in the United Kingdom, 2011. *Comparative Immunology, Microbiology & Infectious Diseases*, *25*(5–6), 331–343. DOI: 10.1016/S0147-9571(02)00030-9.

[72] Mohamed, F., et.al. (2011). Foot-and-mouth disease in feral swine: Susceptibility and transmission. *Transboundary Emerging Diseases*, *58*(4), 358–371. DOI: 10.1111/j.1865-1682.2011.01213.x.

[73] Weaver, G., Domenech, J., Thiermann, A., Karesh, W. (2013). Foot and mouth disease: A look from the wild side. *J. of Wildlife Diseases, 49*(4). Retrieved from https://doi.org/10.7589/2012-11-276.

[74] OIE. (2013). Foot and Mouth Disease. In *Technical Disease Card*. Retrieved from http://www.oie.int.

[75] OIE. (2019). Foot-and-Mouth Disease. In *Terrestrial Animal Health Code* (8.8.). Retrieved from http://www.oie.int.

[76] Yang, P.C., Chu, R.M., Chung, W.B., & Sung, H.T. (1999). Epidemiological characteristics and financial costs of the 1997 foot-and-mouth disease epidemic in Taiwan. *Veterinary Record*, *145*(25), 731–734. DOI: 10.1136/vr.145.25.731.

[77] Kitching, R.P. & Hughes, G.J. (2002). Clinical variation in foot and mouth disease: sheep and goats. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 505–512. DOI: 10.20506/rst.21.3.1342.

[78] Kitching, R.P. & Alexandersen, S. (2002). Clinical variation in foot and mouth disease: pigs. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 513–518. DOI: 10.20506/rst.21.3.1367.

of clinical signs.[79,80]

1.4.5.1 Infectious Dose

Different animal species vary in their susceptibility to FMDV, which is also influenced by the route of infection. Table 1-2 lists the infectious dose and mode of infection for key animals, given the primary mode of transmission for that species.

Table 1-2. Infectious Dose and Mode of Transmission

Species	Infectious Dose	Common Mode
Cattle[81]	May be as low as 20 $TCID_{50}$	Inhalation
Sheep and goats[82]	May be as low as 20 $TCID_{50}$	Direct contact
Pigs[83]	Approximately $log10^5$ $TCID_{50}$	Ingestion

Note: $TCID_{50}$ = 50 percent tissue culture infectious dose.

1.4.6 Morbidity and Mortality

The morbidity and mortality of FMD varies depending on the species affected, as well as the serotype and strain of the virus. Morbidity is significant, and can approach 100 percent.[84] Mortality is typically low in adult animals (1 to 5 percent), though higher mortality rates are typically observed in very young animals, usually from acute myocarditis.[85]

1.4.6.1 Clinical Signs

FMDV is typically characterized by high morbidity, evidenced by characteristic vesicles on the oral and nasal mucosa, teats, coronary bands, and interdigital spaces. However, before vesicles appear, a decreased appetite progresses as fever develops.[86] The clinical signs can vary based on the serotype and strain of the FMDV. Generally speaking, sheep and goats typically have milder

[79] Gay, C.G., et al. (2010). Foot-and-Mouth Disease (FMD): Gap Analysis Workshop Report. In *Agricultural Research Service*. Retrieved from http://go.usa.gov/kCqF.
[80] Orsel, K., et al. (2009) Foot and mouth disease virus transmission during the incubation period of the disease in piglets, lambs, calves, and dairy cows. *Preventive Veterinary Medicine*, *88*(2), 158–163. DOI: 10.1016/j.prevetmed.2008.09.001.
[81] Kitching, R.P. & Hughes, G.J. (2002). Clinical variation in foot-and-mouth disease: cattle. *Scientific and Technical Review of the Office International des Epizooties*, 21(3), 499–504. DOI: 10.20506/rst.21.3.1343.
[82] Kitching, R.P. & Hughes, G.J. (2002). Clinical variation in foot and mouth disease: sheep and goats. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 505–512. DOI: 10.20506/rst.21.3.1342.
[83] Kitching, R.P. & Alexandersen, S. (2002). Clinical variation in foot and mouth disease: pigs. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 513–518. DOI: 10.20506/rst.21.3.1367.
[84] OIE. (2013). Foot and Mouth Disease. In *Technical Disease Card*. Retrieved from http://www.oie.int.
[85] Musser, J.M. (2004). A practitioner's primer on foot-and-mouth disease. *Journal of the American Veterinary Medical Association*, *224*(8), 1261–1268. DOI: 10.2460/javma.2004.224.1261.
[86] Musser, J.M. (2004). A practitioner's primer on foot-and-mouth disease. *Journal of the American Veterinary Medical Association*, *224*(8), 1261–1268. DOI: 10.2460/javma.2004.224.1261.

clinical signs than cattle.[87] The following sections provide more detail on the clinical signs in cattle, pigs, and sheep and goats.

1.4.6.1.1 Cattle

Cattle usually present with fever, anorexia, shivering, and reduction in milk production for approximately 2–3 days, before vesicular lesions are observable on mucous membranes, interdigital spaces, and on the coronary band. The vesicles will rupture in approximately 1 day, and recovery occurs in 8–15 days. Excessive salivation is often observed in cattle and milk yields are reduced by 80 percent.[88,89,90]

1.4.6.1.2 Pigs

In pigs, severe lesions typically are observed on the feet, as well as on the snout, udder, as well as hock and elbow. Excessive salivation is less likely in pigs than in cattle, and lesions in the mouth are milder than those observed elsewhere.[91,92]

1.4.6.1.3 Sheep and Goats

Fewer clinical signs are seen in sheep and goats. Mouth lesions are often not obvious, though lesions can develop on heel bulbs and on the coronary band.[93] Sheep and goats may be important in transmission, as infection presents with mild clinical signs and may not be as immediately recognized.[94]

1.5 Environmental Persistence of FMDV

FMDV is moderately stable in the environment.[95] The FMD virus is susceptible to both acid and alkaline pH. However, under certain conditions, it can maintain infectivity in the environment for extended periods of time. Presence of organic matter increases its persistence.

[87] Musser, J.M. (2004). A practitioner's primer on foot-and-mouth disease. *Journal of the American Veterinary Medical Association*, *224*(8), 1261–1268. DOI: 10.2460/javma.2004.224.1261.
[88] OIE. (2013). Foot and Mouth Disease. In *Technical Disease Card*. Retrieved from http://www.oie.int.
[89] Musser, J.M. (2004). A practitioner's primer on foot-and-mouth disease. *Journal of the American Veterinary Medical Association*, *224*(8), 1261–1268. DOI: 10.2460/javma.2004.224.1261.
[90] Knight-Jones, T. & Rushton, J. (2013). The economic impacts of foot and mouth disease—What are they, how big are they and where do they occur? *Preventive Veterinary Medicine*, *112* (3–4), 161–173. DOI: 10.1016%2Fj.prevetmed.2013.07.013.
[91] Musser, J.M. (2004). A practitioner's primer on foot-and-mouth disease. *Journal of the American Veterinary Medical Association*, *224*(8), 1261–1268. DOI: 10.2460/javma.2004.224.1261.
[92] Kitching, R.P. & Alexandersen, S. (2002). Clinical variation in foot and mouth disease: pigs. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 513–518. DOI: 10.20506/rst.21.3.1367.
[93] Kitching, R.P. & Hughes, G.J. (2002). Clinical variation in foot and mouth disease: sheep and goats. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 505–512. DOI: 10.20506/rst.21.3.1342.
[94] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[95] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.

Table 1-3. Resistance of FMDV to Physical and Chemical Action

Action	Resistance
Temperature	Preserved by refrigeration and freezing. Progressively inactivated by temperatures above 50 ºC. Heating meat to a minimum core temperature of 70 ºC for at least 30 minutes inactivates the virus.
pH	Quickly inactivated by pH <6.0 or >9.0.
Disinfectants	Inactivated by sodium hydroxide (2%), sodium carbonate (4%), citric acid (0.2%), acetic acid (2%), sodium hypochlorite (3%), potassium peroxymonosulfate/sodium chloride (1%), and chlorine dioxide. Resistant to iodophores, quaternary ammonium compounds, and phenol, especially in the presence of organic matter.
Survival	Survives in lymph nodes and bone marrow at neutral pH, but destroyed in muscle at pH <6.0, i.e., after rigor mortis. Survives in frozen bone marrow or lymph nodes. Residual virus survives in milk and milk products during regular pasteurization, but is inactivated by ultra-high temperature pasteurization. Survives drying but may persist for days to weeks in organic matter under moist and cool temperatures. Can persist in contaminated fodder and the environment for up to 1 month, depending on the temperature and pH conditions.

Source: OIE Technical Disease Card for FMD, April 2013.

Sunlight does not have a significant effect on FMDV infectivity.[96] FMDV can be found in the bone marrow, lymph nodes, and certain organs of deceased animals for extended periods of time because the pH does not decline sufficiently after death.[97]

1.5.1 Environmental Persistence of FMDV in Excretions and Surroundings

Under certain environmental conditions, FMDV can survive for significant periods on organic material. Reported survival times of FMDV include up to 20 weeks on hay, 4 weeks in cow's hair in temperate temperatures, 14 days in dry feces, 39 days in urine, 6 months in slurry (winter), and 28 days in soil (fall).[98] FMDV has also been recovered from bovine semen, and can maintain virus titers if frozen at −50 ºC for up to 320 days.[99]

1.5.2 Environmental Persistence of FMDV in Milk and Dairy Products

Raw milk and milk products have the potential to cause infection in animals if not properly treated. Even with a typical pasteurization process, milk and milk products can still be infective to naïve animals.[100] Typical pasteurization processes do not activate FMDV.

[96] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[97] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[98] Alexandersen, S., et al. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.
[99] Cottral, G.E. (1969). Persistence of foot-and-mouth disease virus in animals, their products and the environment. *Scientific and Technical Review of the Office International des Epizooties*, *71*(3–4), 549–568.
[100] Tomasula, P.M. & Konstance, R.P. (2004). The survival of foot-and-mouth disease virus in raw and pasteurized milk and milk products. *Journal of Dairy Science*, *87*(4), 1115–1121. DOI: 10.3168/jds.S0022-0302(04)73258-0.

In milk, experiments have demonstrated that FMDV[101]

- survived in skim milk after heating to 72 ºC for 2 minutes,
- survived in whole milk after heating to 72 ºC for 5 minutes, and
- survived in cream after heating to 93 ºC for 15 seconds.

Additionally, here are some examples of the experimental resistance of FMDV in cheese:[102]

- Survived in Camembert cheese for 21 days at 2 ºC.
- Survived processing for Cheddar cheese prepared from heated milk (but 30 days of curing inactivated the virus).
- Survived processing and curing for Cheddar cheese prepared from unheated milk for 60 days.

FMDV can also survive in other products, such as butter and butter oil, for extended periods (at least 45 days with storage at 4 ºC).[103] However, FMDV has not been detected in whey constituents after processing.[104]

1.5.3 Environmental Persistence of FMDV in Meat and Meat Products

FMDV can maintain infectivity for months in chilled or frozen lymph nodes (beef), liver, and blood. FMDV was detected at 11 days in beef frozen after slaughter and at 4 months in frozen liver.[105] In salted bacon, FMDV was detected at 190 days and in pork sausages at 56 days.[106]

1.5.4 Environmental Persistence of FMDV in Wool and Hides

FMDV can survive on many materials. FMDV has been identified in wool 5-days post-exposure, but was not recovered at measureable amounts from wool stored at 37 ºC after 40–96 hours, or wool stored at 18 ºC after 10–14 days, based on the strain.[107] In hides, FMDV has been detected for 32 days or longer, depending on the humidity and temperature of drying and storage. For example, hides salted and stored at 4 ºC still had detectable FMDV at 352 days; hides dried at 20 ºC, 40 percent relative humidity had detectable FMDV at 42 days.[108]

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[101] Blackwell, J.H. & Hyde, J.L. (1976). Effect of heat on foot-and-mouth disease virus (FMDV) in the components of milk from FMDV-infected cows. *Journal of Hygiene*, *77*(1), 77–83. DOI: 10.1017/s0022172400055534.
[102] Blackwell, J.H. (1976). Survival of Foot-and-Mouth Disease Virus in Cheese. *Journal of Dairy Science*, *59*(9), 1574–1579. DOI: 10.3168/jds.S0022-0302(76)84407-4.
[103] Blackwell, J.H. (1978). Persistence of foot-and-mouth disease virus in butter and butter oil. *Journal of Dairy Science*, *45*(2), 283–285. DOI: 10.1017/S0022029900016460.
[104] Blackwell, J.H. (1978). Potential transmission of foot-and-mouth disease in whey constituents. *Journal of Food Protection*, *41*(8), 631–633. Retrieved from http://www.ingentaconnect.com/content/iafp/jfp/1978/00000041/00000008/art00006.
[105] Ryan, E., et al. (2008). Foot-and-mouth disease virus concentrations in products of animal origin. *Transboundary Emerging Diseases*, *55*(2), 89–98. DOI: 10.1111/j.1865-1682.2007.01004.x.
[106] Ryan, E., et al. (2008). Foot-and-mouth disease virus concentrations in products of animal origin. *Transboundary Emerging Diseases*, *55*(2), 89–98. DOI: 10.1111/j.1865-1682.2007.01004.x.
[107] McColl, K.A., et al. (1995). The persistence of foot-and-mouth disease virus on wool. *The Australian Veterinary Journal*, *72*(8), 286–292. DOI: 10.1111/j.1751-0813.1995.tb03556.x.
[108] Gailiunas, P. & Cottral, G.E. (1967). Survival of foot and mouth disease virus in bovine hides. *American Journal of Veterinary Research*, *28*(125), 1047–1053.

1.6 OIE Procedures for the Inactivation of FMDV

The following sections detail OIE recommended inactivation procedures for FMDV in various animal products. For details on products listed here, please see the *OIE Terrestrial Animal Health Code* (2019).[109]

1.6.1 Meat

Article 8.8.31 in the 2019 *OIE Terrestrial Animal Health Code* provides the following procedures for the inactivation of FMDV in meat and meat products:

1. Canning

   Meat and meat products are subjected to heat treatment in a hermetically sealed container to reach an internal core temperature of at least 70 ºC for a minimum of 30 minutes or to any equivalent treatment which has been demonstrated to inactivate FMDV.

2. Thorough cooking

   Meat, previously deboned and defatted, and meat products are subjected to heat treatment so that an internal temperature of 70 ºC for a minimum of 30 minutes.

   After cooking, they should be packed and handled in such a way that it cannot be exposed to a source of FMDV.

3. Drying after salting

   When *rigor mortis* is complete, the meat must be deboned, salted with cooking salt (NaCl) and 'completely dried'. It must not deteriorate at ambient temperature.

   'Completely dried' is defined in terms of the ration between water and protein which must not be greater than 2.25:1 or a water activity (Aw) that is not greater than 0.85.

1.6.2 Wool and Hair

Article 8.8.32 in the 2019 *OIE Terrestrial Animal Health Code* provides the following procedures for the inactivation of FMDV in wool and hair:

> For the inactivation of viruses present in wool and hair for industrial use, one of the following procedures should be used:
>
> 1. industrial washing, which consists of the immersion of the wool in a series of baths of water, soap, and sodium hydroxide (soda) or potassium hydroxide (potash);
> 2. chemical depilation by means of slaked lime or sodium sulphide;
> 3. fumigation in formaldehyde in a hermetically sealed chamber for at least 24 hours;

[109] OIE. (2019). Foot-and-Mouth Disease. In *Terrestrial Animal Health Code* (8.8.). Retrieved from http://www.oie.int.

4. industrial scouring which consists of the immersion of wool in a water-soluble detergent held at 60–70 ºC;
5. storage of wool at 18 ºC for four weeks, or 4 ºC for four months or 37 ºC for eight days.

1.6.3 Milk and Cream for Human Consumption

Article 8.8.35 in the 2019 *OIE Terrestrial Animal Health Code* provides the following procedures for the inactivation of FMDV in milk and cream for human consumption:

> For the inactivation of FMDV present in milk and cream for human consumption, one of the following procedures should be used:
>
> 1. a process applying a minimum temperature of 132 ºC for at least one second (ultra-high temperature [UHT]), or
> 2. if the milk has a pH less than 7.0, a process applying a minimum temperature of 72 ºC for at least 15 seconds (high temperature-short time pasteurization [HTST]), or
> 3. if the milk has a pH of 7.0 or over, the HTST process applied twice.

1.6.4 Milk for Animal Consumption

Article 8.8.36 in the 2019 *OIE Terrestrial Animal Health Code* provides the following procedures for the inactivation of FDMV in milk for animal consumption:

> For the inactivation of FMDV present in milk for animal consumption, one of the following procedures should be used:
>
> 1. the HTST process applied twice; or
> 2. HTST combined with another physical treatment, e.g. maintaining a pH 6 for at least one hour or additional heating to at least 72 ºC combined with desiccation; or
> 3. UHT combined with another physical treatment referred to in point 2 above.

Attachment 1.A References and Selected Resources

Adams, R.L.P., Knowler, J., & Leader, D. (1992). The structure of viruses. *The biochemistry of the nucleic acids* (p.75–76). United Kingdom: Chapman & Hall. DOI: 10.1007/978-94-011-2290-0.

Alexandersen, S., Zhang, Z., & Donaldson, A.I. (2002). Aspects of the persistence of foot-and-mouth disease virus in animals—the carrier problem. *Microbes and Infection*, *4*(10), 1099–1110. DOI: 10.1016/S1286-4579(02)01634-9.

Alexandersen, S., Zhang, Z., Donaldson, A.I., & Garland, A.J. (2003). The pathogenesis and diagnosis of foot-and-mouth disease. *Journal of Comparative Pathology*, *129*(1), 1–36. DOI: 10.1016/S0021-9975(03)00041-0.

Amass, S., Pacheco, J., Mason, P., Pacheco, J., Miller, C., Ramirez, A., Clark, L., Ragland, D., Schneider, J., & Kenyon, S. (2004). Procedures for preventing transmission of foot-and-mouth disease virus (O/TAW/97) by people. *Veterinary Microbiology*, *103*(3–4), 143–149. DOI: 10.1016/j.vetmic.2004.07.020.

Amass, S., Pacheco, J., Mason, P., Schneider, J., Alvarez, R., Clark, L., & Ragland, D. (2003). Procedures for preventing the transmission of foot-and-mouth disease virus to pigs and sheep by personnel in contact with infected pigs. *Veterinary Record*, *153*(5), 137–140. DOI: 10.1136/vr.153.5.137.

Anderson, E.C., Doughty, W.J., Anderson, J., & Paling, R. (1979). The pathogenesis of foot-and-mouth disease in the African buffalo (*Syncerus caffer*) and the role of this species in the epidemiology of the disease in Kenya. *Journal of Comparative Pathology*, *89*(4), 541–549. DOI: 10.1016/0021-9975(79)90045-8.

Belsham, G. & Bøtner, A. (2015). Use of recombinant capsid proteins in the development of a vaccine against foot-and-mouth disease virus (FMDV). *Virus Adaptation and Treatment*, *7*, 11–23. DOI: 10.2147/VAAT.S55351.

Bertram, M. et al. (2020). Extinction dynamics of the foot-and-mouth disease virus carrier state under natural conditions. Front. Vet. Sci., 20 May 2020. Retrieved from https://doi.org/10.3389/fvets.2020.00276.

Blackwell, J.H. (1976). Survival of Foot-and-Mouth Disease Virus in Cheese. *Journal of Dairy Science*, *59*(9), 1574–1579. DOI: 10.3168/jds.S0022-0302(76)84407-4.

Blackwell, J.H. (1978). Persistence of foot-and-mouth disease virus in butter and butter oil. *Journal of Dairy Science*, *45*(2), 283–285. DOI: 10.1017/S0022029900016460.

Blackwell, J.H. (1978). Potential transmission of foot-and-mouth disease in whey constituents. *Journal of Food Protection*, *41*(8), 631–633. Retrieved from http://www.ingentaconnect.com/content/iafp/jfp/1978/00000041/00000008/art00006.

Blackwell, J.H. & Hyde, J.L. (1976). Effect of heat on foot-and-mouth disease virus (FMDV) in the components of milk from FMDV-infected cows. *Journal of Hygiene*, *77*(1), 77–83. DOI: 10.1017/s0022172400055534.

Bravo de Rueda, C., et al. (2014). Identification of factors associated with increased excretion of foot-and-mouth disease virus. *Prev. Vet. Med. 113*(1). DOI: 10.1016/j.prevetmed.2013.10.005. Retrived from https://doi.org/10.1016/j.prevetmed.2013.10.005.

Bronsvoort, B. M. d. et al. (2016). Redefining the "carrier" state for foot-and-mouth disease from the dynamics of virus persistence in endemically affected cattle populations. Sci. Rep. 6, 29059. DOI: 10.1038/srep29059. Retrieved from https://www.nature.com/articles/srep29059.

Center for Food Security and Public Health (CFSPH). (2014). Foot-and-Mouth Disease. In *Technical Factsheet.* Retrieved from www.cfsph.iastate.edu.

Condy, J.B., Hedger, R.S., Hamblin, C., & Barnett, I.T. (1985). The duration of the foot-and-mouth disease virus carrier state in African buffalo (i) in the individual animal and (ii) in a free-living herd. *Comparative Immunology, Microbiology & Infectious Diseases*, *8*(3–4), 259–265. DOI: 10.1016/0147-9571(85)90004-9.

Cottral, G.E. (1969). Persistence of foot-and-mouth disease virus in animals, their products and the environment. *Scientific and Technical Review of the Office International des Epizooties*, *71*(3–4), 549–568.

Davies, G. (2002). The foot and mouth disease epidemic in the United Kingdom, 2011. *Comparative Immunology, Microbiology & Infectious Diseases*, *25*(5–6), 331–343. DOI: 10.1016/S0147-9571(02)00030-9.

Donaldson, A.I. (1972). The influence of relative humidity on the aerosol stability of different strains of foot and mouth disease virus suspended in saliva. *Journal of General Virology*, *15*(1), 25–33. DOI: 10.1099/0022-1317-15-1-25.

Donaldson, A.I. (1983). Quantitative data on airborne foot-and-mouth disease virus; its production, carriage, and deposition. *In Philosophical Transactions of the Royal Society of London, Series B, 302*(1111), 529–534. DOI: 10.1098/rstb.1983.0072.

Donaldson, A.I. (2008). Foot-and-mouth disease and the use of face masks. *Veterinary Record*, *162*(5), 163. DOI: 10.1136/vr.162.5.163.

Donaldson, A.I. & Alexandersen, S. (2002). Predicting the spread of foot and mouth disease by airborne virus. *Scientific and Technical Review of the Office International des Epizooties (Paris)*, *21*(31), 569–575. DOI: 10.20506/rst.21.3.1362.

Donaldson, A.I., Herniman, K.A., Parker, J., & Sellers, R.F. (1970). Further investigations on the airborne excretion of foot-and-mouth disease virus. *Journal of Hygiene, 68*(4), 557–564. DOI: 10.1017/s0022172400042480.

Donaldson A.I. & Kitching, R.P. (1989). Transmission of foot-and-mouth disease by vaccinated cattle following natural challenge. *Research in Veterinary Science*, *46*(1),

9–14.

Forman, A.J. & Gibbs, E.P.J. (1974). Studies with foot-and-mouth disease virus in British deer (red, fallow, and roe): 1. Clinical Disease. *Journal of Comparative Pathology*, *84*(2), 215–220. DOI: 10.1016/0021-9975(74)90062-0.

Gailiunas, P. & Cottral, G.E. (1967). Survival of foot and mouth disease virus in bovine hides. *American Journal of Veterinary Research*, *28*(125), 1047–1053.

Gay, C.G., Borca, M., Capozzo, A., De Clercq, K., Elsken, L., Espinoza, A., Hammond, H., Konig, G., Leon, E., Mattion, N., Metwally, S., Perez-Filgueira, M., Perez, A., Rieder, E., Smitsaart, E., Vosloo, W., Art, J., Brake, D., Duque, H., Golde, W., Grubman, M., Krug, P., Lombard, M., McIntosh, M., & Rodriguez, L. (2010). Foot-and-Mouth Disease (FMD): Gap Analysis Workshop Report. In *Agricultural Research Service*. Retrieved from http://go.usa.gov/kCqF.

Goodwin, S., Tuthill, T.J., Arias, A., Killington, R.A., & Rowlands, D.J. (2009). Foot-and-mouth disease virus assembly: processing of recombinant capsid precursor by exogenous protease induces self-assembly of pentamers in vitro in a myristoylation-dependent manner. *Journal of Virology*, *83*(21), 11275–11282. DOI: 10.1128/JVI.01263-09.

Hugh-Jones, M.E. & Wright, P.B. (1970). Studies on the 1967–8 foot-and-mouth disease epidemic: The relation of weather to the spread of disease. *Journal of Hygiene*, *68*(2), 253–271. DOI: 10.1017/s0022172400028722.

International Committee on Taxonomy of Viruses. (2019). Foot-and-Mouth Disease. Retrieved from https://talk.ictvonline.org/ictv-reports/ictv_online_report/positive-sense-rna-viruses/picornavirales/w/picornaviridae/707/genus-aphthovirus.

Kitching, R.P. (2002). Identification of foot and mouth disease virus carrier and subclinically infected animals and differentiation from vaccinated animals. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 531–538. DOI: 10.20506/rst.21.3.1365.

Kitching, R.P. & Alexandersen, S. (2002). Clinical variation in foot and mouth disease: pigs. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 513–518. DOI: 10.20506/rst.21.3.1367.

Kitching, R.P. & Hughes, G.J. (2002). Clinical variation in foot-and-mouth disease: cattle. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 499–504. DOI: 10.20506/rst.21.3.1343.

Kitching, R.P. & Hughes, G.J. (2002). Clinical variation in foot and mouth disease: sheep and goats. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 505–512. DOI: 10.20506/rst.21.3.1342.

Knight-Jones, T. & Rushton, J. (2013). The economic impacts of foot and mouth disease—What are they, how big are they and where do they occur? *Preventive Veterinary Medicine*, *112* (3–4), 161–173. DOI: 10.1016%2Fj.prevetmed.2013.07.013.

Lubroth, J., Yedloutschnig, R.J., Culhane, V.K., & Mikiciuk, P.E. (1990). Foot-and-mouth disease virus in the llama (*Lama glama*): diagnosis, transmission, and susceptibility. *Journal of Veterinary Diagnostic Investigation*, *2*(3), 197–203. DOI: 10.1177/104063879000200308.

McColl, K.A., Westbury, H.A., Kitching, R.P., & Lewis, V.M. (1995). The persistence of foot-and-mouth disease virus on wool. *The Australian Veterinary Journal*, *72*(8), 286–292. DOI: 10.1111/j.1751-0813.1995.tb03556.x.

McVicar, J.W., Sutmoller, P., Ferris, D.H., & Campbell, C.H. (1974). Foot-and-mouth disease in white tailed deer: clinical signs and transmission in the laboratory. In *Proceedings of the 78th annual meeting of the United States Animal Health Association* (p. 169–180).

Mohamed, F., Swafford, S., Petrowski, H., Bracht, A., Schmit, B., Fabian, A., Pacheco, J.M., Hartwig, E., Berninger, M., Carrillo, C., Mayr, G., Moran, K., Kavanaugh, D., Leibrecht, H., White, W., Metwally, S. (2011). Foot-and-mouth disease in feral swine: Susceptibility and transmission. *Transboundary Emerging Diseases*, *58*(4), 358–371. DOI: 10.1111/j.1865-1682.2011.01213.x.

Morris, R.S., Sanson, R.L., Stern, M.W., Stevenson, M., Wilesmith, J.W. (2002). Decision-support tools for foot and mouth disease control. *Scientific and Technical Review of the Office International des Epizooties*, *21*(3), 557–567.

Musser, J.M. (2004). A practitioner's primer on foot-and-mouth disease. *Journal of the American Veterinary Medical Association*, *224*(8), 1261–1268. DOI: 10.2460/javma.2004.224.1261.

Orsel, K., Bouma, A., Dekker, A., Stegeman, J.A., & de Jong, M.C. (2009) Foot and mouth disease virus transmission during the incubation period of the disease in piglets, lambs, calves, and dairy cows. *Preventive Veterinary Medicine*, *88*(2), 158–163. DOI: 10.1016/j.prevetmed.2008.09.001.

Ryan, E., Mackay, D., & Donaldson, A. (2008). Foot-and-mouth disease virus concentrations in products of animal origin. *Transboundary Emerging Diseases*, *55*(2), 89–98. DOI: 10.1111/j.1865-1682.2007.01004.x.

Sellers, R.F., Donaldson, A.I., & Herniman, K.A. (1970). Inhalation, persistence and dispersal of foot-and-mouth disease virus by man. *Journal of Hygiene* (London), *68*(4), 565–573. DOI: 10.1017/s0022172400042492.

Sellers, R.F., Herniman, K.A., & Mann, J.A. (1971). Transfer of foot-and-mouth disease virus in the nose of man from infected to non-infected animals. *Veterinary Record*, *89*(16), 447–449. DOI: 10.1136/vr.89.16.447-a.

Shors, T. (2013). Baltimore classification. In *Understanding viruses* (56). Burlington, MA: Jones & Bartlett Learning.

Stenfeldt., C., et al. (2016). Detection of foot-and-mouth disease virus RNA and capsid protein in lymphoid tissues of convalescent pigs does not indicate existence of a carrier state. *Transbound Emerg Dis. 63*(2). DOI:10.1111/tbed.12235. Retrieved from

https://onlinelibrary.wiley.com/doi/full/10.1111/tbed.12235.

Stenfeldt, C. & Arzt, J. (2020). The Carrier Conundrum; A Review of Recent Advances and Persistent Gaps Regarding the Carrier State of Foot-and-Mouth Disease Virus. *Pathogens 2020, 9*(3), 167. Retrieved from https://doi.org/10.3390/pathogens9030167.

Stenfeldt, C., Eschbaumer, M., Rekant, S.I., Pacheco, J.M., Smoliga, G.R., Hartwig, E.J.,Rodriguez, L.L., Arzt, J. (2016). The foot-and-mouth disease carrier state divergence in cattle. *J. Virol. 90*, 6344–6364. Retrived from https://jvi.asm.org/content/90/14/6344.

Sutmoller, P. & Casas-Olascoga, R. (2002). Unapparent foot and mouth disease infection (sub-clinical infections and carriers): implications for control. *Scientific and Technical Review of the Office International des Epizooties, 21*(3), 519–529. DOI: 10.20506/rst.21.3.1366.

Sutmoller, P., McVicar, J.W., & Cottral, G.E. (1968). The epizootiological importance of foot-and-mouth disease carriers. I: Experimentally produced foot-and-mouth disease carriers in susceptible and immune carriers. *Archives of Virology*, *23*(3), 227–235. DOI: 10.1007/BF01241895.

Tenzin, Dekker, A., Vernooij, H., Bouma, A., & Stegeman, A. (2008). Rate of foot-and-mouth disease virus transmission by carriers quantified from experimental data. *Risk Analysis*, *28*(2), 303–309. DOI: 10.1111/j.1539-6924.2008.01020.x.

Thomson, G. R. (1996). The role of carrier animals in the transmission of foot and mouth disease. In *OIE comprehensive reports on technical items presented to the International Committee or to Regional Commissions* (p. 87–103). Retrieved from http://www.oie.int/doc/ged/D3014.PDF.

Tomasula, P.M. & Konstance, R.P. (2004). The survival of foot-and-mouth disease virus in raw and pasteurized milk and milk products. *Journal of Dairy Science*, *87*(4), 1115–1121. DOI: 10.3168/jds.S0022-0302(04)73258-0.

United States Department of Agriculture (USDA), Animal and Plant Health Inspection Service (APHIS), Animal Health. (2020). *Animal Health Status of Regions*. Retrieved from https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/animal-and-animal-product-import-information/animal-health-status-of-regions.

Weaver, G., Domenech, J., Thiermann, A., Karesh, W. (2013). Foot and mouth disease: A look from the wild side. *J. of Wildlife Diseases, 49*(4). Retrieved from https://doi.org/10.7589/2012-11-276.

World Organization for Animal Health (OIE). (2013). Foot and Mouth Disease. In *Technical Disease Card*. Retrieved from http://www.oie.int.

World Organization for Animal Health (OIE). (2019). Foot-and-Mouth Disease. In *Terrestrial Animal Health Code* (8.8.). Retrieved from http://www.oie.int.

World Organization for Annimal Health (OIE)/Food and Agriculture Organization (FAO) Foot-and-Mouth Disease Reference Laboratory Network. (2018). Annual Report. Retrieved from:

https://www.foot-and-mouth.org/sites/foot/files/user-files/research-paper/pdf/11-19/OIE-FAO%20FMD%20Ref%20Lab%20Network%20Report%202018.pdf.

World Organization for Animal Health (OIE). (2020). Foot-and-Mouth Disease. *List of Members with endorsed official control programme for FMD*. Retrieved from https://www.oie.int/animal-health-in-the-world/official-disease-status/fmd/fmd-official-control-programme/.

Yang, P.C., Chu, R.M., Chung, W.B., & Sung, H.T. (1999). Epidemiological characteristics and financial costs of the 1997 foot-and-mouth disease epidemic in Taiwan. *Veterinary Record*, *145*(25), 731–734. DOI: 10.1136/vr.145.25.731.

Attachment 1.B Abbreviations

APHIS	Animal and Plant Health Inspection Service
CFSPH	Center for Food Security and Public Health
FAD PReP	Foreign Animal Disease Preparedness and Response Plan
FMD	foot-and-mouth disease
FMDV	foot-and-mouth disease virus
HTST	high temperature-short time (pasteurization)
NAHEMS	National Animal Health Emergency Management System
OIE	World Organization for Animal Health
RNA	ribonucleic acid
SAT	South African Territories (serotypes of FMD)
SOP	standard operating procedure
TCID	tissue culture infectious dose
TDD	telecommunications device for the deaf
UHT	ultra-high temperature (pasteurization)
USDA	United States Department of Agriculture
WAHID	World Animal Health Information Database
WAHIS	World Animal Health Information System