Chapter 5

Host Range, Host–Virus Interactions, and Virus Transmission

Gustavo Fermin
Universidad de Los Andes, Mérida, Venezuela

> *Of living things, my son, some are made friends with fire, and some with water, some with air, and some with earth, and some with two or three of these, and some with all.*
>
> Hermes Trismegistus

Where there is life, there are viruses. For more than a decade, it is clear from ecological studies, and more recently from metagenomic studies, that viruses represent the major part of the modern biosphere; and there is no reason to assume that the same situation did not exist before the **l**ast **u**niversal **c**ommon **a**ncestor (LUCA) in the RNA world. Many of the viruses today are entirely dependent upon their host's cells for their survival and replication. It is erroneous, or extremely naïve, to believe that viruses depend solely on chance for their replication and dissemination. They have developed the ability not only to replicate in their host, but also to move between host cells and ultimately between hosts in order to persist. Indeed, viruses have the remarkable ability to spread from one host to another host, hosts that belong to the three cellular domains of life—Archaea, Bacteria, and Eukarya. This constitutes their host range. Viruses known to infect one or a limited number of species are said to be specialists; whereas those that infect a wide range of hosts, are referred to as generalists. While water and air are very good vehicles for the transportation and spread of many viruses, those viruses that infect eukaryotes often depend on different types of organisms to work as vectors and to facilitate host-to-host spread. Either way, viruses establish

Viruses. DOI: https://doi.org/10.1016/B978-0-12-811257-1.00005-X

relationships with their hosts that encompass all symbiotic associations along the mutualism—parasitism continuum. What we presently know appears to be just the tip of the iceberg. Very recently, it was reported that mammals carry cytoplasmic replicons that might represent an antediluvian virus-derived symbiont. Circular DNA molecules associated with TSE (**t**ransmissible **s**pongiform **e**ncephalopathies) preparations and normal mammalian tissues were found capable of replicating symbiotically in mammalian brain cells. The circular DNA molecules, designated as SPHINX sequences using an acronym given for **S**low **P**rogressive **H**idden **IN**fections of variable (X) latency, show similarities to an *Acinetobacter* phage and possibly represent remnant phage DNAs of commensal *Acinetobacter*. *Acinetobacter* sp. are adapted to a variety of habitats, including soil, and are commonly found in association with humans, animals, and insects. They easily gain entry into animals while grazing or drinking water. These findings lead to a number of questions of how this type of association between a mammalian host and phage virus originated, how it is maintained and whether SPHINX was incorporated during mammalian evolution. More importantly, the findings suggest that mammals share and exchange a larger world of prokaryotic viruses than previously realized.

This chapter provides an overview of the concept of virus host range including the various interactions a virus can initiate and maintain with different hosts. We focus on the strategies adopted by viruses in order to achieve new targets of replication, along with their abiotic and biotic vehicles of dissemination.

DEFINING THE HOST RANGE

The host range, a key property of viruses, reflects the diversity of species that viruses can naturally infect. To be a member of the exclusive "*host range*" club of a virus, the host should support the replication or life cycle of the virus; i.e., the virus should be able to successfully enter a host cell and complete a series of tasks, including unencapsidation and replication in the initial cell and movement to adjacent cells and throughout the host. Nonetheless, it is often difficult to define the host range of a virus as a number of other factors need to be incorporated, such as the host susceptibility to infection, as well as the ability of the virus to undergo sustained transmission from host to host. Moreover, the actual breadth of the host range can be reduced by barriers that prevent contact between vectors and hosts, and the unsynchronized seasonal timing between (1) available infected hosts in a viremic stage and feeding activity of vectors and (2) available uninfected species and infectious vectors in a given environment. And it can be expanded. Depending on the virus, the range may expand to secondary hosts and/or vectors, as a result of selection pressure on the virus generated either in vectors or in hosts as well as of the degree of promiscuity of host seeking behavior of the vectors involved. Moreover, other viruses, such as rhabdoviruses, replicate in their insect vectors. Thus the majority of known rhabdovirus species have two natural hosts, either insects and plants, or insects and vertebrates. The virus host range is also expanded when there are "*spillover*" infections into alternative hosts. In some instances, viruses gain the ability to spread efficiently to a new host that was not previously exposed or susceptible (see the section on zoonosis). These transfers involve either increased exposure or the acquisition of genetic variations that allow the virus to overcome barriers to infection of the new host. Phylogenetic studies suggest that these host shifts are frequent in the evolution of most pathogens, but why viruses successfully jump between some host species but not others is only just becoming clear.

For these reasons, the host range is highly variable among viruses. Some, such as dengue and mumps viruses, whose only known mammalian host are humans, are referred to as specialist viruses. These viruses have evolved to become specialized in infecting one or very few host species. In contrast, generalist viruses successfully infect hosts from different species and even hosts from a higher taxonomical rank. Examples of generalist viruses include *Cucumber mosaic virus* (CMV; *Bromoviridae*), which infects more than 1000 plant species, and *Influenza A virus* (*Orthomyxoviridae*), which infects birds and several different species of mammals. Opinions have been divided regarding the evolutionary significance of host range variation. Some argue that host–virus relationships with a narrow, specific host range are more advanced, while others posit the opposite. The advantages of generalism are more obvious: a generalist virus would be able to exploit multiple hosts and thus enhance its fitness. Since generalist viruses are not the norm, it is generally assumed that generalism comes with a cost. It has also been suggested that evolution should favor specialists because evolution proceeds faster with narrower niches. The answers may lie with genome sequencing. Through genome sequencing, it is now apparent that a variety of organisms carry genes that reflect past infection events by viruses. By using data from multiple potential host species, it may be possible to determine whether extant viruses characterized as presently having a broad host range have been resident in the genomes of their hosts for longer times than current viruses with a narrow host range. Such evidence may suggest that families of viruses with broad host ranges are more evolutionarily ancient, and may have benefited from a greater ability to avoid extinction. Also, it is increasing clear that understanding the evolution and biology of a species cannot be achieved without examining the interactions between the members of the holobiont; i.e., the prokaryotic symbionts, the eukaryotic symbionts, the viruses, and the host. Metagenomics, coupled with biological studies, promise further characterization of these host–virus interactions.

INTERACTIONS BETWEEN A VIRUS AND ITS HOST(S) MAY HAVE DIFFERENT OUTCOMES

Though studies into the entire spectrum of virus—pathogen interactions are still in their infancy, there has been a recent spurt in studies exploring the possibility of a number of symbiotic interactions, not limited to parasitism and disease. More and more evidence is accumulating on the existence of viruses that are essential for the survival of their hosts; viruses that are beneficial and their net effects on the host are positive. The interaction of a virus and its host is being redefined as a two-way biological relationship, which in most cases, if not all, is modulated by the prevailing conditions. In other words, these biological interactions are described in terms of the effects they have on both partners under particular conditions, and the impact on either species can be neutral, positive, or negative. The relationships are not always static, they vary under different conditions, and the magnitude of the effects are continuous instead of discrete. Outside the field of virology, categorization of biological interactions is still controversial; in virology, it is even more so.

It is widely accepted that many of the viruses we know are host-dependent parasites that can cause disease (see Chapters 6—9: Viruses as Pathogens: Plant Viruses, Viruses as Pathogens: Animal Viruses, With Emphasis on Human Viruses, Viruses as Pathogens: Animal Viruses Affecting Wild and Domesticated Species, and Viruses of Prokaryotes, Protozoa, Fungi, and Chromista). By hijacking the metabolism of the infected host in order to fulfill their needs of replication, local and systemic movement and transmission from host to host, a virus causes severe impairments in the physiology of the host; in some cases, leads to the death of the cell or the organism. However, virus—host interactions do not always yield hallmark phenotypic symptoms of viral infections and can influence hosts in which they reside. Case in point a recent study reported direct virus-metazoan symbiosis limiting pathogenic bacterial growth on mucosal surfaces, a phenomenon apparently conserved from cnidarians to humans. Additionally, integration or domestication of viral genetic elements that benefits the host are well illustrated by examples of prophages in bacteria. These interactions are further described in Chapter 11, Beneficial Interactions With Viruses.

In other instances it is very difficult, if not impossible, to categorize host/virus interactions in only one manner. For example, CMV (*Bromoviridae*) is an important plant pathogen with the widest host-range of all known plant viruses, and worldwide distribution. The virus is transmitted by no less than 60 different species of aphids, or via seeds or dodder. Although the virus can dramatically affect the physiology of the infected host ("*intended*" target) where it acts like a true pathogen, its effect on the aphid vector ("*nonintended*" target) is quite different. Depending on the titer of the virus, elicitation of plant defense responses by CMV leads to a reduction of aphid performance; but additionally, some wingless aphids become winged so contributing to virus dissemination. That is, the virus negatively affects its plant host, but at the same time affects its animal host (the biological vector of its dissemination) in a way that we cannot deem *detrimental*. In other kind of interactions, the outcome is very different. Endoparasitoid insects spend part of their development in other invertebrates, e.g., some lepidopteran wasp species. In order to avoid the defense responses of the parasitized organism, endoparasitoid wasps use various mechanisms to ensure the successful development of their larvae. One of such mechanism depends on the presence of viruses that are injected during wasp oviposition. These viruses hosted by the wasps neutralize or decrease the lepidopteran wasp-host defense systems thus enabling the development of eggs and larvae of the endoparasitoid. Interestingly, however, *Diadromus pulchellus toursvirus* (*Ascoviridae*) behaves differently in other wasp species. That is, like a pathogen (negative effect) in *Itoplectis tunetana*, a commensal (neutral effect) in various species of *Eupelmus* and *Dinarmus*, or like a mutualist (positive effect, as mentioned earlier) in *Diadromus pulchellus* and *D. collaris*. Finally, it has been proposed that a shift in the human gut bacteriophage community composition can contribute to a shift from health to disease. Although not a host of bacteriophages, the human receives benefit from the existence of free phages that help in modulating its bacteriome. If *Escherichia virus Lambda* (*Siphoviridae*), e.g., lyses its host (say *Escherichia coli*), and "*free*" virions adsorb to the human gut, they might lyse unwanted bacteria that are part of their host-range. We are not hosting the virus, but we receive some benefit derived from its presence.

THE MANY WAYS OF VIRUS TRANSMISSION

Undoubtedly, one of the critical challenges to initiating the viral replication cycle in a host lies with the virus' ability to overcome multiple barriers as it moves from cell-to-cell to tissue-to-tissue within the host organism and from organism-to-organism, and even across species. In this section, we examine the characteristics and fundamental differences between these types of transmission.

Cell-to-Cell Transmission

Viruses are able to translocate their virions or genomes between neighboring cells via intercellular connections. In plants and algae, cell-to-cell transmission of viruses (local movement) is accomplished by means of plasmodesmata—narrow, intercellular cytoplasmic bridges that connect and enable communication between adjacent cells. In order to overcome the physical constraints imposed by the exclusion size of plasmodesmata, viruses encode a protein, called the movement protein, that dilates plasmodesmata openings to enable the passage of viral nucleic-acid–protein complexes (*Cucumovirus*, *Potyvirus*) or whole virions (*Comovirus*, *Closterovirus*). In some plant viruses, the viral coat protein and replicase also play a role in virus movement through plasmodesmata. Many viruses subsequently utilize the phloem transport system to systemically infect their hosts. *Tobacco mosaic virus* (TMV), e.g., enters minor, major, and transport veins from nonvascular cells in source tissue and exit from veins into sink tissue. In other cases, like *Turnip mosaic virus* (*Potyviridae*) and *Potato virus X* (*Alphaflexiviridae*), systemic infection of the plant is attained by the virus moving through xylem vessels.

Cell-to-cell transmission, and systemic spread, of animal viruses is achieved in two ways: diffusion through the extracellular space (cell-free transmission) or by direct cell-to-cell contact. The first route, cell-free transmission, requires the dissociation of progeny particles from the infected cell either by lysis or exocytosis. This leads to viremia and enables passive dissemination of virus through blood fluids to distant tissues. Lymphatic vessels are one of the principal routes of virus passage from exposed surfaces (skin, respiratory mucosa, and digestive tract) into the interior of the animal body, but blood vessels constitute the main route of dissemination, and represent the source from which hematophagous arthropods obtain the virus for transmission host-to-host. Although this route can allow spread across long distances within the host and permits an easier spread to a new host, the second route involving cell—cell transmission is an effective way of avoiding the various physical and immunological barriers within the organism. In cell-to-cell transmission, virus can use preexisting cell interactions (e.g., neurological or immunological synapses), or viruses can deliberately establish transient cell—cell contact between infected cells and uninfected target cells. In the latter instance, a **v**irological **s**ynapse (VS), i.e., a tight cleft between an infected cell and a target cell is formed as a result of firmly adhering plasma membranes of the two opposing cells. In HIV-1, e.g., assembly of the HIV-1 T-cell VS requires engagement of the HIV-1 Env surface subunit gp120, expressed on the infected cell, with its cellular receptors CD4 and CXCR4 on the target cell, followed by further recruitment of receptors and HIV-1 proteins to the conjugate interface by a cytoskeleton-dependent process in both target and infected T cells. Subsequent clustering of adhesion molecules (such as the integrin leukocyte function-associated antigen 1) presumably contributes to the formation of a stable adhesive junction. HIV-1 and other viruses (Human T-cell lymphotropic virus type 1) utilize both methods of cell—cell transmission. Others, use either existing cell interactions (herpesviruses and rhabdoviruses) or form a VS. Another means of cell-to-cell spread involves the use of actin-rich cellular structures that propel virions from infected cells directly into uninfected cells (poxviruses) and breaking down intercellular barriers by inducing limited membrane fusion between infected and uninfected cells (paramyxoviruses).

Virus Survival in the Environment

Viruses are often shed into the environment from infected hosts or carrier hosts. Bacteriophages, an example of the most abundant of all viruses, can be found not only associated with bacterial host cells, humans, and other animals, but also in deserts, hot springs, warm and cold seas, ground and surface water, soil, food, sewage, and sludge. They are carried by urine, feces, blood, serum, and saliva as well as in the air. Other nonphage viruses, enveloped and nonenveloped (representing various taxonomic groups), are likely present in similar environmental media. It is not an exaggeration to say that viruses are everywhere. While outside of their cellular hosts and in the environment, viruses have the potential to survive, persist, and be transported by various routes to other susceptible hosts. Not all viruses released into the environment are, however, successful in maintaining an infectious status and reaching new susceptible hosts; persistence or survival can vary greatly with virus type and environmental conditions.

In order to survive in the environment, virions must cope with a number of physical, chemical, and biological factors. UV radiation from the sun is the main virucide in the environment. Loss of infectious capacity or inactivation of DNA and RNA viruses primarily occurs in the long-wave (UV-A) range (320–400 nm). This damage is mostly due to chemical changes in the nucleic acids and the formation of pyrimidine dimers; DNA is more susceptible than RNA. Other factors affecting the survival of viruses in the environment include temperature, acidity, salinity, and ions. Of the viruses, phages are most resistant to a range of conditions. Some members of the families *Myoviridae*, *Podoviridae*, and *Siphoviridae* are resistant to highly dry environments and can endure a range of temperature fluctuations and remain infectious after several years. Others are stable under acidic (*Fuselloviridae*, *Tectiviridae*, and *Lipothrixviridae*) or alkaline conditions (*Leviviridae*). For other viruses, it is generally accepted that enveloped viruses are more sensitive to degradation and persist poorly in the environment (as desiccation of viral lipid envelopes typically reduces infectivity) than naked viruses. However, a study investigating enveloped surrogates of coronaviruses (transmissible gastroenteritis and mouse hepatitis) demonstrated that these enveloped viruses remained infectious in wastewater for weeks. Additionally, enveloped influenza viruses have been detected in sewage. Perhaps more environmental persistence studies are warranted rather than a general assumption of negligible persistence.

The survival of free viruses in the environment (an estimated half-life of 48 h in most ecosystems) is of the outmost importance from an epidemiological point of view. A virus found in the air, water, soil, the remains of an infected living being, food, and inanimate surfaces (fomites) can invariably find a way of entry to a susceptible host. Even more, sometimes a nonhost, nonvector animal (e.g., cockroaches) can carry viruses that contribute to infections of true hosts. From the virus' point of view, the window of opportunity for transmission depends crucially on the longevity of infectious stages in the environment. Thus viruses have adapted their life cycles and developed sophisticated strategies to optimize their transmission to new susceptible hosts. Some viruses are transmitted vertically to host offspring and others are transmitted by contact between hosts (e.g., by wind, water, or physical contact), but most viruses rely on vectors for rapid dissemination within host populations.

Horizontal Transmission

At its simplest, transmission is defined as the means by which an infectious agent is passed from an infected host to a susceptible host. It is a function of both the host and the pathogen and consists of pathogen presentation by the host, movement between infected and healthy hosts, and entry into the new host. Transmission dynamics may involve varying degrees of complexity, from single-host species (measles- or rubella viruses) to contrasting multiple host species (*Rift Valley fever phlebovirus*, *Phenuiviridae*). Further, viruses are able to use, simultaneously or sequentially, multiple modes of transmission, including but not exclusive to vertical or horizontal transmission. In vertical transmission, viruses are passed vertically from mother to offspring. In horizontal transmission, viruses are transmitted among individuals of the same generation which encompasses both direct and indirect modes. Horizontal transmission can be further classified as direct or indirect. Horizontal transmission by a direct route includes airborne infection, food-borne infection, and venereal (sexual) infection, whereas transmission by an indirect route involves an intermediate or an inanimate object (fomite) or a biological host, like a mosquito vector, which acquires and transmits virus from one host to another. Table 5.1 summarizes the known modes of transmission of viruses. Viruses that use biological vectors are given in Table 5.2.

Airborne Viruses

Like cellular microorganisms, viruses are ubiquitously found in the air. Viruses can become airborne only if conditions for aerosolization are met (mass, size, shape, and density, among others). An aerosol is a particle suspension in a gaseous medium, e.g., the air. A virus can be naturally aerosolized primarily by sneezing, or secondarily, when an infected surface serves as the source of air transportation by means of other mechanical processes, like splashing, bubbling, sprinkling or even toilet flushing. Human (seasonal) behavior (personal hygiene, closed environments, densely populated areas, transportation hubs, and pollution) is regarded as an important contributor to the spread of viruses by aerosols. Additionally, viruses can be aerosolized by coughing flying animals (bats and birds, for instance); droppings can also serve as a primary source of viruses than can later be secondarily transmitted by air. In the case of *Foot-and-mouth disease virus* (*Picornaviridae*), e.g., computer simulations have estimated that "*in a worst case scenario*" cattle could be infected as far as 20–300 km far from the infectious source.

TABLE 5.1 Transmission Modes of Viruses

Viral Family	Hosts[a]	Transmission	Vector[b]
Adenoviridae	A	Respiratory droplets; orofecal route	N
Alloherpesviridae	A	Passive diffusion	N
Alphaflexiviridae	F–P	Mechanical; vector; grafting; others unknown	Y/N
Alphatetraviridae	A	Oral route. Vertical transmission also possible	N
Amalgaviridae	P	Vertically through seeds; horizontally undocumented	?
Ampullaviridae	Ar	Passive diffusion	N
Anelloviridae	A	Sexual, blood, saliva; possibly also orofecal route and maternal transmission	N
Arenaviridae	A	Zoonosis (saliva, urine, nasal secretions of rodents); fomites; aerosol. Vertically: transuterine, transovarian. Milk, saliva, urine	N
Arteriviridae	A	Genital and respiratory tract secretions; transplacental; urine, semen; probably contact; aerosol	N
Ascoviridae	A	Mechanical; vector. Vertically during oviposition	Y
Asfarviridae	A	Mechanically by biting flies. Contact, fomites, ingestion	Y
Astroviridae	A	Orofecal route	N
Avsunviroidae	P	Mechanical. Seeds; vegetative propagation	N
Baculoviridae	A	Orofecal route; contamination of egg surface. Vertically from infected male or female parent to the egg	N
Barnaviridae	F	Transmission is horizontal via mycelium and possibly basidiospores	N
Benyviridae	P	Mechanical; vector	Y

(*Continued*)

TABLE 5.1 (Continued)

Viral Family	Hosts[a]	Transmission	Vector[b]
Betaflexiviridae	F–P	Mechanical; vector; seeds; grafting, propagating material	Y/N
Bicaudaviridae	Ar	Passive diffusion; vertically by lysogeny	N
Bidnaviridae	A	Oral route?	?
Birnaviridae	A	Horizontally by contact. Vertical transmission also in salmonids	N
Bornaviridae	A	Fomites; direct contact with salivary, conjunctival and nasal secretions, urine and feces	N
Bromoviridae	P-F	Mechanical; vector. Pollen (carried by thrips)	Y
Caliciviridae	A	Direct contact with infected individual; feces, vomitus or respiratory secretions; contaminated food, water, and fomites	N
Carmotetraviridae	A	Oral route	N
Caulimoviridae	A–P	Mechanical; vector; grafting, wounds, seeds, vegetative propagation, dodders	Y
Chrysoviridae	F	Intracellularly during cell division; sporogenesis and cell fusion	N
Circoviridae	A	Orofecal route. Vertical transmission also reported	N
Clavaviridae	Ar	Passive diffusion	N
Closteroviridae	P	Some by mechanical inoculation; propagative material, dodder, grafting. Others by vector	Y/N
Coronaviridae	A	Respiratory droplets, orofecal route, oronasal route, fomites	N
Corticoviridae	B	Passive diffusion	N
Cystoviridae	B	Pilus adsorption	N
Dicistroviridae	A	Contaminated food. Vertically in aphids; horizontally by means of plants (passive reservoir for Cripaviruses). Vector	Y/N
Endornaviridae	C–F–P	Transmission during mitosis, and via pollen and ova in plants	N

Filoviridae	A	Zoonosis; contact with body fluids, blood or injured skin	N
Fimoviridae	P	Grafting; vector	Y
Flaviviridae	A	Sex; blood, semen. Zoonosis (rodents, bats); arthropod bite. Unknown in some. Vertical: transplacental. Transplantation, nonpasteurized milk, aerosols. Indirect contact: urine or nasal secretions, feces, contaminated food	Y/N
Fuselloviridae	Ar	Passive diffusion; vertically by lysogeny	N
Geminiviridae	P	Vector	Y
Genomoviridae	A–F–P	Some vectored; others unknown	Y
Globuloviridae	Ar	Passive diffusion	N
Guttaviridae	Ar	Passive diffusion	N
Hantaviridae	A	Zoonosis (rodents: urine, saliva. Bites); fomites; contact	N
Hepadnaviridae	A	Parental (perinatal transmission), sexual, blood, open skin breaks or mucous membranes. Infection in ovo (birds)	N
Hepeviridae	A	Zoonosis (pigs and others); fomites. Orofecal route; contaminated water	N
Herpesviridae	A	Contact with lesions and body fluids (urine, saliva); sexual; infection at birth by a genitally-infected mother; respiratory route; transplacentary, transplantation, blood transfusion	N
Hypoviridae	F	Cell-to-cell; cytoplasmic exchange; hyphal anastomosis. Conidia	N
Hytrosaviridae	A	Horizontal; food contamination. Vertical: mother to offspring	N
Inoviridae	B	Pilus adsorption	N
Iridoviridae	A	Contact; cannibalism in invertebrates; vector. Cohabitation, feeding or wounding	Y/N
Lavidaviridae	Pr	Passive diffusion?	N

(*Continued*)

TABLE 5.1 (Continued)

Viral Family	Hosts[a]	Transmission	Vector[b]
Leviviridae	B	Pilus adsorption	N
Lipothrixviridae	Ar	Passive diffusion; some pili dependent. Vertically by lysogeny	N
Luteoviridae	P	Mechanical, vector	Y
Malacoherpesviridae	A	Passive diffusion; contact while larvae; experimentally by intramuscular injection	N
Marnaviridae	C	Passive diffusion	N
Marseilleviridae	Pr–A	Passive diffusion. Some water- and soilborne	N
Megabirnaviridae	F	Through hyphal anastomosis; cytoplasmic exchange	N
Metaviridae	A–F–P	Retrotransposons. Vertical transmission only, or cell-to-cell	N
Microviridae	B	Pilus adsorption	N
Mimiviridae	Pr	Passive diffusion	N
Myoviridae	Ar–B	Passive diffusion; vertically by lysogeny	N
Nairoviridae	A	Zoonosis; vector. Some by fomites	Y/N
Nanoviridae	P	Vector	Y
Narnaviridae	C–F–Pr	Horizontally through mating or vertically from mother to daughter cells (no extracellular stage of the virus). Conidia and ascospores	N
Nimaviridae	A	Contact. By predation or cannibalism on diseased animals or via water through the gills. Vertically from nonviable infected eggs or from supporting cell in ovarian tissue	N
Nodaviridae	A	Passive diffusion; direct contact. Vector. Vertical transmission in fishes	Y/N
Nudiviridae	A	Feeding and/or mating route	N
Nyamiviridae	A	Undocumented. May be vectored. In wasps vertical transmission to the progeny	Y

Ophioviridae	P	Mechanical; vegetative propagation. Some are transmitted by zoospores of *Olpidium brassicae*, a root-infecting fungus. *Citrus psorosis virus* rather seems to be propagated by an aerial vector, or grafting	Y/N
Orthomyxoviridae	A	Aerosols (coughing); birds droppings. Zoonosis. Contact with saliva, nasal secretions, feces or blood. In birds: orofecal route. Waterborne (e.g., *Isavirus*). Interspecies infection possible	Y/N
Papillomaviridae	A	Close contact, including sex	N
Paramyxoviridae	A	Contact: feces, secretions from mouth, nose, eyes. Aerosols. Zoonosis; animal bites?	N
Partitiviridae	F–P	Cell division (but not cell-to-cell); sporogenesis; cytoplasmic exchange; hyphal anastomosis. Seeds (*Cryptovirus*)	N
Parvoviridae	A	Respiratory, oral droplets or orofecal route	N
Peribunyaviridae	A	Zoonosis; arthropod bites	Y
Permutotetraviridae	A	Oral route	N
Phenuiviridae: Phasivirus	A	Zoonosis	N
Phenuiviridae: Phlebovirus	A	Zoonosis; arthropod bites	Y
Phenuiviridae: Tenuivirus	P	Mechanical inoculation, usually by an insect	Y
Phycodnaviridae	A–C–P	Passive diffusion. Phaeoviruses are transmitted both horizontally and vertically	N
Picobirnaviridae	A	Orofecal route	N
Picornaviridae	A	Orofecal and respiratory (aerosol) routes; contact; saliva; blood; respiratory secretions. Zoonosis; fomites. Ingestion of virus-contaminated material (*Cardiovirus*)	N
Plasmaviridae	B	Undocumented. Vertically by lysogeny	N

(*Continued*)

TABLE 5.1 (Continued)

Viral Family	Hosts[a]	Transmission	Vector[b]
Pleolipoviridae	Ar	Passive diffusion	N
Pneumoviridae	A	Respiratory secretions	N
Podoviridae	B	Passive diffusion; vertically by lysogeny; some pili dependent	N
Polydnaviridae	A	Vertically transmitted to the offspring as provirus. Horizontally by oviposition in the host larvae	N
Polyomaviridae	A	Orofecal route, contaminated feces and aerosolized dust, hand to mouth. Egg transmission in birds. Human transplantation	N
Pospiviroidae	P	Mechanical. Vegetative propagation. Vector	Y/N
Potyviridae	P	Mechanical, grafting, vector	Y
Poxviridae	A	Direct contact, aerosol or fomites. Some mechanical by arthropod bites	Y/N
Pseudoviridae	A–F–P–Pr	Almost exclusively vertically. Yeast: by conjugation	N
Quadriviridae	F	Cytoplasmic exchange; hyphal anastomosis; sporogenesis. Cell division	N
Reoviridae	A–F–P	Ingestion and surface of eggs (*Cypovirus*); enteric or respiratory routes (*Orthoreovirus*); passive diffusion (*Aquareovirus*); delphacid planthoppers (*Oryzavirus* and *Fijivirus*-also with vegetative propagation); ticks, blood transfusion (*Coltivirus*). Orbivirus: ticks, gnats, phlebotomines, mosquitoes; *in utero* in some vertebrates. *Rotavirus*: orofecal route. *Seadornavirus*: mosquitoes. *Phytoreovirus*: cicadellid leafhoppers	Y/N
Retroviridae	A	Cell-to-cell, airborne; fluids (including blood, milk, and saliva), developing embryo; perinatal routes. Vertically: endogenous provirus (up to 10% of genomic DNA in some vertebrates), but no virions produced	N
Rhabdoviridae	A–P	Zoonosis; animal bites, midges, sandflies, mosquitoes. Passive diffusion; contact. Waterborne. Mechanical inoculation: aphid, leafhopper, planthopper, fungi. Transovarial transmission in insects	Y/N

Roniviridae	A	Passive diffusion. By ingestion of infected material or water. Vertical	N
Rudiviridae	Ar	Passive diffusion	N
Secoviridae	P	Mechanical inoculation; vector: insects or nematodes; some seed or pollen	Y
Siphoviridae	Ar–B	Passive diffusion; vertically by lysogeny	N
Sphaerolipoviridae	Ar–B	Passive diffusion	N
Spiraviridae	Ar	Passive diffusion	N
Tectiviridae	B	Passive diffusion	N
Togaviridae	A	Respiratory (aerosol). Zoonosis; arthropod bite	Y/N
Tolecusatellitidae	P	By vectors of begomoviruses (their helper viruses)	Y
Tombusviridae	P	Mechanical, plant contact, seed, propagating material. Water- and soilborne (stable and infectious). Vector	Y/N
Tospoviridae	P	Arthropod bites; vector	Y
Totiviridae	F–Pr	Passive diffusion, sporogenesis, cell division an fusion	N
Turriviridae	Ar	Passive diffusion	N
Tymoviridae	A–P	Mechanical; vector; poorly by seeds; propagating material	Y
Unassigned: *Cilevirus*	P	Vector	Y
Unassigned: *Deltavirus*	A	Sexual contact, blood, maternal-neonatal	N
Unassigned: *Idaeovirus*	P	Pollination (i.e., pollen-associated); seeds. Mechanical	N

(*Continued*)

TABLE 5.1 (Continued)

Viral Family	Hosts[a]	Transmission	Vector[b]
Unassigned: *Ourmiavirus*	P	Mechanical; undocumented vector	N
Unassigned: *Polemovirus*	P	Grafting; vegetative propagation. Maybe by soil. Vector undocumented	N
Unassigned: *Rhizidiovirus*	C–F	Passive diffusion. Vertically by zoospores of the host *Rhizidiomyces* sp.	N
Unassigned: *Salterprovirus*	Ar	Passive diffusion	N
Unassigned: *Sobemovirus*	P	Mechanical. Vector. Seedborne	Y/N
Virgaviridae	P	Mechanical. Vector. Seeds, pollen. Leaf contact	Y/N

[a] Hosts are defined here as species of the seven kingdoms of life whose members can be infected and support replication of viruses belonging to the families listed in the first column: A (Animalia), Ar (Archaea), B (Bacteria), C (Chromista), F (Fungi), P (Plantae), and Pr (Protozoa).
[b] Vectors are living organisms that carry virions from one infected host to the other (Y); if no vector is known for any member of a family the letter "N" is used; in cases where a virus can be transmitted as an alternative mode of transmission, or some members of the same family are vectored by a living organism while others are not, "Y/N" is used. Most common vectors are listed in Table 5.2. No information was available for the virus families *Alvernaviridae, Feraviridae, Gammaflexiviridae, Iflaviridae, Jonviridae, Phasmaviridae, Sarthroviridae, Solinviviridae, Sunviridae and Tristromaviridae the genus Goukovirus of the family Phenuiviridae, and the unassigned genera Albetovirus, Anphevirus, Arlivirus, Aumaivirus, Bacilladnavirus, Bacillarnavirus, Blunervirus, Botybirnavirus, Chengtivirus, Crustavirus, Dinodnavirus, Higrevirus, Labyrnavirus, Mesoniviridae, Mymonaviridae, Papanivirus, Sinaivirus, Tilapinevirus, Virtovirus and Wastrivirus.*

TABLE 5.2 Examples of Viruses and Their Vectors

Virus Family (Genus)	Hosts[a]	Type of Vector (Some Examples)
Alphaflexiviridae (*Allexivirus*)	P	Arachnids: Mites (*Aceria tulipae*)
Alphaflexiviridae (*Potexvirus*)	P	Insects: Aphids (if a potyvirus provides a helper protein), or buff-tailed bumblebees (*Bombus terrestris*) in greenhouse
Ascoviridae (*Ascovirus*)	A	Insects: Endoparasitic wasps (e.g., *Campoletis sonorensis, Diadegma semiclausum, Microplitis similis, M. croceipes, Toxoneuron nigriceps*)
Ascoviridae (*Toursvirus*)	A	Insects: Endoparasitic wasps (e.g., *Diadromus pulchellus*)
Asfarviridae (*Asfivirus*)	A	Arachnids: Argasid ticks (reservoir) of the genus *Ornithodoros*
		Insects: flies and bugs (genera *Simulium, Stomoxys,* and *Triatoma*)
Benyviridae (*Benyvirus*)	P	Plasmodiophorids: *Polymyxa betae* and *P. graminis*
Betaflexiviridae (*Carlavirus*)	P	Insects: Aphids or whiteflies (*Bemisia tabaci*)
Betaflexiviridae (*Trichovirus*)	P	Arachnids: Mites (*Colomerus vitis, Eriophyes inequalis, E. insidiosus*)
Betaflexiviridae (*Vitivirus*)	P	Insects: Pseudococcid mealybugs (genera *Pseudococcus* and *Planococcus*), scale insects (*Neopulvinaria innumerabilis*), and aphids
Bromoviridae (*Alfamovirus*)	P	Insects: Aphids (*Myzus persicae* and at least 13 more species belonging to the family Aphididae)
Bromoviridae (*Bromovirus*)	P	Insects: Beetles (although with low efficiency). For example, *Diabrotica undecimpunctata howardi* for *Cowpea chlorotic mottle virus*
Bromoviridae (*Cucumovirus*)	P	Insects: Aphids (genera *Aphis, Myzus*) Fungi: *Cucumber mosaic virus* in *Rhizoctonia solani*
Caulimoviridae (*Badnavirus*)	P	Insects: Aphids, mealybugs (*Planococcus citri*), and lacebugs

(*Continued*)

TABLE 5.2 **(Continued)**

Virus Family (Genus)	Hosts[a]	Type of Vector (Some Examples)
Caulimoviridae (*Caulimovirus*)	P	Insects: Aphids (e.g., *Chaetosiphon fragaefolii*)
Caulimoviridae (*Tungrovirus*)	P	Insects: Leafhoppers of the genera *Nephotettix* and *Recilia* (if a waikavirus provides a helper protein)
Closteroviridae (*Ampelovirus*)	P	Insects: Pseudococcid mealybugs and soft scale insects (*Ceroplastes, Coccus, Dysmicoccus, Heliococcus, Pulvinaria, Neopulvinaria, Parasaissetia, Parthenolecanium, Phenacoccus, Planococcus, Pseudococcus*, and *Saissetia*)
Closteroviridae (*Closterovirus*)	P	Insects: Many different species of aphids (e.g., *Myzus persicae, Aphis citricidus, A. fabae*, and *A. gossypii*)
Closteroviridae (*Crinivirus*)	P	Insects: Whiteflies of the genera *Bemisisa* and *Trialeurodes*
Dicistroviridae (*Aparavirus*)	A	Arachnids: Mites (*Varroa destructor*). Probably fire ants too
Fimoviridae (*Emaravirus*)	P	Arachnids: Possibly the mite *Eriophyes pyri*
Flaviviridae (*Flavivirus*)	A	Insects: Mosquitoes (genera *Aedes, Anopheles, Armigeres, Coquillettidia, Culex, Culicoides, Culiseta, Eretmapodites, Haemagogus, Mansonia, Mimomya*, and *Toxorhynchites*), flies (genera *Musca* and *Phlebotomus*), and bugs (*Cimex*)
		Arachnids: Ticks (genera *Amblyomma, Argas, Dermacentor, Haemaphysalis, Hyalomma, Ixodes*, and *Rhipicephalus*)
Geminiviridae (*Begomovirus*)	P	Insects: Whiteflies (mainly *Bemisisa tabaci*; also reported: *Aleurotrachelus socialis*)
Geminiviridae (*Capulavirus*)	P	Insects: Aphids (*Aphis craccivora*)
Geminiviridae (*Curtovirus*)	P	Insects: Leafhoppers (*Circulifer tenellus*)
Geminiviridae (*Grablovirus*)	P	Insects: Treehoppers (*Spissistilus festinus*)

Geminiviridae (*Mastrevirus*)	P	Insects: Leafhoppers (mostly of the genus *Cicadulina*). Also *Nesoclutha declivata* has been proposed for *Digitaria streak virus*
Geminiviridae (*Topocuvirus*)	P	Insects: Treehoppers (*Micrutalis malleifera*)
Geminiviridae (*Turncurtovirus*)	P	Insects: Leafhoppers (*Circulifer haematoceps*)
Genomoviridae (*Gemycircularvirus*)	F	Insects: Flies (*Lycoriella ingenua*). This virus genus has members that mostly infect animals and plants
Iridoviridae (*Ranavirus*)	A	Insects: parasitic wasps; maybe the mosquitoe *Aedes* sp. as vector to terrestrial turtles, and *Culex territans* or *Lasiohelea* in bullfrogs; parasitic nematodes (e.g. *Thaumamermis cosgrovei*)
Iridoviridae (*Chloriridovirus*)	A	Nematodes: *Strelkovimermis spiculatus*, as vector of *Invertebrate iridescent virus 3* to *Culex pipiens*
Luteoviridae (*Enamovirus*)	P	Insects: Aphids (genera *Acyrthosiphon, Myzus*)
Luteoviridae (*Luteovirus*)	P	Insects: Aphids (genera *Myzus, Schizaphis*)
Luteoviridae (*Polerovirus*)	P	Insects: Aphids (genera *Aphis, Macrosiphum, Myzus, Schizaphis*)
Nairoviridae (*Orthonairovirus*)	A	Arachnids: Argasid and ixodid ticks
Nanoviridae (*Babuvirus*)	P	Insects: Aphids (*Pentalonia nigronervosa, Micromyzus kalimpongensis*)
Nanoviridae (*Nanovirus*)	P	Insects: Aphids (*Aphis craccivora, A. fabae, A. gossypii, Acyrthosiphon pisum, Megoura viciae*)
Nodaviridae (*Alphanodavirus*)	A	Insects: *Aedes aegypti* (to suckling mice)
Nyamiviridae (*Nyavirus*)	A	Arachnids: Ticks (e.g., *Ornithodoros coriaceus*)
Ophioviridae (*Ophiovirus*)	P	Fungi: Zoospores of *Olpidium brassicae*
Orthomixoviridae (*Quaranjavirus*)	A	Arachnids: Ticks (genera *Ornithodoros* and *Argas*)

(*Continued*)

TABLE 5.2 (Continued)

Virus Family (Genus)	Hosts[a]	Type of Vector (Some Examples)
Orthomyxoviridae (*Thogotovirus*)	A	Arachnids: Ticks (genera *Ornithodoros, Hyalomma, Amblyomma,* and *Ripicephalus*)
		Insects: Mosquitoes (genera *Aedes* and *Culex*)
Peribunyaviridae (*Orthobunyavirus*)	A	Arachnids: Ticks, and Insects: mosquitoes, culicoid flies (*Culicoides*), phlebotomines
Phenuiviridae (*Phlebovirus*)	A	Insects: Mosquitoes (genera, *Aedes, Anopheles, Coquillettidia, Culex, Culicoides, Eretmapodites, Mansonia,* and *Toxorhynchites*), flies (*Lutzomia* and *Stomoxys*)
		Arachnids: Ticks (genera *Boophilus, Hyalomma* and *Rhipicephalus*)
Phenuiviridae (*Tenuivirus*)	P	Insects: Planthoppers (genera *Caenodelphax, Javesella, Laodelphax, Nilaparvata, Peregrinus, Sogatella, Tagosodes,* and *Unkanodes*)
Pospiviroidae (*Pospiviroid)*	P	Insects: Aphids (*Myzus persicae* for *Potato spindle tuber viroid,* only if *Potato leafroll virus* (*Luteoviridae*) is present, and *Tomato planta macho viroid*)
Potyviridae (*Brambyvirus*)	P	Unknown: Presumably transmitted by an aerial vector yet to be identified
Potyviridae (*Bymovirus*)	P	Plasmodiophorids: For example, *Polymyxa graminis*
Potyviridae (*Ipomovirus*)	P	Insects: Whiteflies (*Bemisia tabaci*)
Potyviridae (*Macluravirus*)	P	Insects: Aphids (e.g., *Rhopalosiphum maidis* and *Myzus persicae*)
Potyviridae (*Poacevirus*)	P	Arachnids: Eriophyid mites (e.g., *Aceria tosichella*)
Potyviridae (*Potyvirus*)	P	Insects: Aphids, more than 200 species including those of the genera *Acyrthosiphon, Aphis, Aulacarthum, Brachycaudus, Brevicoryne, Hysteroneura, Hyalopterus, Hyperomyzus, Macrosiphum, Metopolophium, Myzus, Phorodon, Rhopalomyzus, Rhopalosiphum, Schizaphis, Sitobion, Therioaphis,* and *Uroleucon.*

Potyviridae (*Rymovirus*)	P	Arachnids: Eriophyid mites (e.g., *Abacarus hystrix*)
Potyviridae (*Tritimovirus*)	P	Arachnids: Eriophyid mites (e.g., *Aceria tosichella*)
Poxviridae (*Avipoxvirus*)	A	Insects: At least 10 different species of mosquitoes (genera *Aedes*, *Anopheles*, *Culex*, *Culiseta*, *Echydnophaga*, and *Stomoxys*); beetles (*Alphitobius*)
		Arachnids: Mites (*Dermanyssus*)
Reoviridae (*Coltivirus*)	A	Insects: Mosquitoes
		Arachnids: Ticks (genera *Dermacentor*, *Haemaphysalis*, *Otobius*, and *Ixodes*)
Reoviridae (*Fijivirus*)	P	Insects: Planthoppers (genera *Delphacodes*, *Dicranotropis*, *Javesella*, *Laodelphax*, *Perkinsiella*, *Ribautodelphax*, *Sogatella*, *Toya*, and *Unkanodes*)
Reoviridae (*Orbivirus*)	A	Insects: Mosquitoes (genera *Aedes*, *Culex*, and *Culicoides*), gnats and phlebotomines
		Arachnids: Ticks (genera *Hyalomma* and *Ornithodoros*)
Reoviridae (*Oryzavirus*)	P	Insects: Planthoppers (some members of the genera *Nilaparvata* and *Sogatella*)
Reoviridae (*Phytoreovirus)*	P	Insects: Leafhoppers (genera *Agallia*, *Agalliopsis*, *Nephotettix*, and *Recilia*)
Reoviridae (*Seadornavirus*)	A	Insects: Mosquitoes (genera *Aedes*, *Anopheles*, and *Culex*)
Rhabdoviridae (*Cytorhabdovirus*)	P	Insects: Aphids (*Acyrtoshiphon*, *Hyperomyzus*, *Macrosiphum*, *Megoura*, and *Myzus*), leafhoppers (e.g., *Endria inimica*, *Recilia dorsalis*), and planthoppers
Rhabdoviridae (*Dichorhavirus*)	P	Arachnids: False spider mites (v. g., *Brevipalpus* spp.)
Rhabdoviridae (*Ephemerovirus*)	A	Insects: Mosquitoes (e.g., genus *Mansonia*) and various *Culicoides* species
Rhabdoviridae (*Ledantevirus)*	A	Insects: Mosquitoes (genera *Aedes*, *Eretmapodites*, and *Culex*) and wingless bat flies (Nycteribiidae family)
		Arachnids: Ticks (*Amblyomma*)

(*Continued*)

TABLE 5.2 **(Continued)**

Virus Family (Genus)	Hosts[a]	Type of Vector (Some Examples)
Rhabdoviridae (*Lyssavirus*)	A	Animal bites: Mainly from bats of the subfamily Desmodontinae (except *Mokola Lyssavirus*), *Canis lupus familiaris, Felis catus, Vulpes vulpes*
Rhabdoviridae (*Nucleorhabdovirus*)	P	Insects: Aphids (genera *Aphis, Hyperomyzus*), planthoppers (like *Peregrinus maidis* and *Ribautodelphax notabilis*), leafhoppers (e.g., genera *Agallia, Graminella,* and *Nesoclutha*)
		Arachnids: Mites
Rhabdoviridae (*Tibrovirus*)	A	Insects: Midges (genus *Culicoides brevitarsis* and *C. insignis*)
Rhabdoviridae (*Tupavirus*)	A	Arachnids: Ticks (genus *Ambylomma*)
Rhabdoviridae (*Varicosavirus*)	P	Fungi: Zoospores of *Olpidium brassicae* and *O. virulentus*
Rhabdoviridae (*Vesiculovirus*)	A	Insects: Mostly sandflies (e.g., *Psathyromyia shannonii*), blackflies and cullicoids, but also lice
		Hirudineans: Leeches
Secoviridae (*Comovirus*)	P	Insects: Beetles (especially members of the family Chrysomelidae; e.g., *Cerotoma trifurcata*)
Secoviridae (*Cheravirus*)	P	Nematodes: For example, *Xiphinema americanum*
		Insects: Aphids and thrips
Secoviridae (*Fabavirus*)	P	Insects: Aphids (e.g., genus *Myzus*)
Secoviridae (*Sequivirus*)	P	Insects: Aphid (*Cavariella aegopodii, C. pastinacae*), leafhoppers
Secoviridae (*Nepovirus*)	P	Nematodes: *Xiphinema, Longidorus* or *Paralongidorus* spp.
		Insects: Aphids and thrips
Secoviridae (*Torradovirus*)	P	Insects: Whiteflies (e.g., *Trialeurodes vaporariorum*)

Secoviridae (*Sadwavirus*)	P	Nematodes: (*Xiphinema diversicaudatum*)
		Insects: Aphids and thrips
Secoviridae (*Waikavirus*)	P	Insects: Aphids and leafhoppers (*Graminella nigrifrons, Nephotettix virescens*)
Togaviridae (*Alphavirus*)	A	Insects: Mosquitoes (genera *Aphis, Haemagogus*)
Tolecusatellitidae (all recognized genera)	P	Insects: *Bemisia tabaci* whiteflies. They are satellites of begomoviruses
Tombusviridae (*Auresusvirus*)	P	Fungi: *Olpidium bornovanus* for *Cucumber leaf spot virus*, and *Polymyxa graminis* for *Maize white line mosaic virus*
Tombusviridae (*Avenavirus*)	P	Fungi: Probably zoosporic fungi (not proven yet)
Tombusviridae (*Carmovirus*)	P	Fungi: *Olpidium bornovanus* for various carmoviruses
Tombusviridae (*Dianthovirus*)	P	Fungi: *Red clover necrotic mosaic virus* may be transmitted by the chytrid fungus *Olpidium* sp.
Tombusviridae (*Machlomovirus*)	P	Insects: Thrips (*Frankliniella williamsi*) and chrysomelid beetles (experimentally)
Tombusviridae (*Necrovirus*)	P	Fungi: *Olpidium brassicae*
Tombusviridae (Tombusvirus)	P	Fungi: *Cucumber necrosis virus* is transmitted by the chytrid fungus *Olpidium bornovanus*
Tombusviridae (*Umbravirus*)	P	Insects: Aphids (e.g., *Acyrtoshiphon* sp.). *Note*: Umbraviruses depends on one particular polerovirus or enamovirus for virion assembly and thus transmission by aphids
Tospoviridae (*Orthotospovirus*)	P	Insects: More than 10 different species of thrips (like *Frankliniella occidentalis, F. schultzei, Scirtothrips dorsalis*, and *Thrips tabaci*)
Tymoviridae (*Marafivirus*)	P	Insects: Leafhoppers (genera *Aconurella, Dalbulus*, and *Macrosteles*)
Tymoviridae (*Tymovirus*)	P	Insects: Beetles (some members of the families Chrysomelidae and Curculionidae)
Virgaviridae (*Furovirus*)	P	Plasmodiophorids: For example, *Polymyxa graminis*

(*Continued*)

TABLE 5.2 (Continued)

Virus Family (Genus)	Hosts[a]	Type of Vector (Some Examples)
Virgaviridae (*Pecluvirus*)	P	Plasmodiophorids: For example, *Polymyxa graminis*
Virgaviridae (*Pomovirus)*	P	Plasmodiophorids: *Spongospora subterranea* and *Polymyxa betae*
Virgaviridae (*Tobravirus*)	P	Nematodes: Members of the genera *Trichodorus* and *Paratrichodorus*
Unassigned: *Cilevirus*	P	Arachnids: Mites (*Brevipalpus* spp.)
Unassigned: *Sobemovirus*	P	Insects: Beetles, aphids (*Illinoia pepperi, Myzus persicae, Rhopalosiphum padi*), garden flea-hoppers (*Halticus citri*), leafminers (*Liriomyza langei*), moths (*Diaphaulaca aulica*), leafhoppers (*Circulifer tenellus*), thrips (*Thrips tabaci*), and mirids (*Cyrtopeltis nicotianae*)

[a] Hosts: A (Animalia), F (Fungi), and P (Plantae).

In no-simulation studies, that distance was demonstrated to reach up to 70 km. Metagenomics studies have detected viruses in the atmosphere, including Pseudomonas phage f10, *Pseudomonas virus F116*, and *Escherichia virus P1* from bacteria, Human adenovirus C, along with circoviruses, nanoviruses, microphage-related, and geminivirus-related (plant) viruses. Of note, more contaminated air (smog) harbors an increased number of viral particles. In near-surface atmosphere of different locations (residential, forest, and industrial settings), airborne viruses that infect animals and plants can also be detected, particularly during winter.

Waterborne Viruses

Water is an excellent medium for the transportation and dissemination of viruses. The oceans are a particularly important habitat of bacterial and archaeal viruses—along with those that infect marine plants, animals, fungi, protozoa, and chromista. Water transmitted animal viral pathogens include adeno-, astro-, rota-, noro-, calici-, and polioviruses, as well as hepatitis viruses; urine secreted viruses that can reach water, like polyoma- and cytomegaloviruses, can also be included in the list of water spread viruses. Evidence on the water dissemination of influenza- and coronaviruses is inconclusive.

In the case of plant viruses, there is accumulating evidence of viruses remaining infectious for sufficiently long periods where they become a threat and can infect important plant crops. Although values vary according to species, virions found in water can remain viable for days and weeks, possibly facilitated by aggregation and/or adsorption to solid materials (e.g., clays and silicates) or to organic debris, bacteria or algae. *Pepino mosaic virus* (PepMV; *Potexvirus*) remains infectious for up to 3 weeks, *Potato virus Y* (PVY; *Potyvirus*) for 1 week, and *Potato spindle tuber viroid* (*Pospiviroid*) for up to 7 weeks in water at $20 \pm 4°C$ under controlled conditions. In the case of PepMV and PVY, virions were released from the roots of infected plants. Further, it has been demonstrated that *Pepper mild mottle virus* (*Tobamovirus*), one of the most abundant RNA viruses in human feces, can be found in sea and ground waters at concentrations that range from 1.7×10^1 to 1×10^4 genome copies per liter. This indicates not only the persistence of viruses in the environment, but the complexity of interactions that can be established between a nonhost mammal and a plant virus that survived the conditions in an animal's gut as well as water. The findings also demonstrate that the virus is a promising indicator of fecal pollution of water bodies. Other plant viruses detected in environmental waters (lakes, rivers, sea, tap, and irrigation waters) belong to the genera *Alphacarmovirus*, *Cucumovirus*, and other genera of the family *Tombusviridae*. When associated with the outer covering of the aquatic zoospores of the fungus *Olpidium* *bornovanus*, virions of *Melon necrotic spot virus* (*Tombusviridae*) remain viable for several years.

Soilborne Viruses

Some viruses are extremely stable under soil conditions. In general, virus survival in soils depends mostly on temperature and virion adsorption to soil (sand and clay colloids). Other influential factors include soil moisture content, presence of aerobic microorganisms, levels of resin-extractable phosphorous, exchangeable aluminum, organic matter, and soil pH. TMV (*Virgaviridae*), for instance, remains infectious in soil for several years in living or dead plant debris. Infections have been reported with plants brought into physical contact with soilborne viruses during transplanting. Although the majority of plant viruses are transmitted by arthropod vectors and invade the host plants through the aerial parts, there is a considerable number of plant viruses that infect roots via soil-inhabiting vectors such as plasmodiophorids, chytrid fungi, and nematodes (see later).

Regarding animal viruses, polioviruses (*Picornaviridae*) are stable in soils provided temperatures are not high (e.g., 3 months at 4°C). At low temperatures and a pH of 7.5, some enteroviruses in soil may survive from 110 to 170 days. *Influenza A virus* (*Orthomyxoviridae*) H5N1 can be found in soil-based composts. Similarly, other animal viruses can be found in soil contaminated with feces, urine, other body fluids, and the carcasses of terrestrial organisms. Bacteriophages have been recovered from saline soils. Virus titers are low in hyper arid desert soils and bacterial lysogens levels are high, in cold desert soils. Most viruses found in the former, however, have yet to be identified and represent uncharacterized virus phylogenetic lineages.

Transplantation, Anastomosis, and Grafting

Of equal significance is the transmission of viruses via allotransplantation. A variety viruses may be transmitted by this route and include *Human immunodeficiency virus 1*, *West Nile virus*, *Human betaherpesvirus 5*, *Rabies lyssavirus* as well as hepatitis B, C, and E viruses. With xenotransplantation (cross-species transfer from pigs to humans), there is a risk of transmitting **p**orcine **e**ndogenous **r**etro**v**iruses (PERVs), **p**orcine **c**yto**m**egalo**v**irus (PCMV), HEV genotype 3, **p**orcine **l**ymphotropic **h**erpes**v**iruses (PLHVs), and **p**orcine **c**irco**v**iruses (PCVs). Only HEV, however, is known to infect humans *in vivo*, while HEV, PCV2, and PERV have been reported to infect human cells *in vitro*.

Similarly, plant viruses are often transmitted by grafting and budding. These centuries-old techniques are used in the vegetative propagation of fruit trees and, in recent decades, vegetable crops. In grafting, the upper shoot (scion) of one plant grows on the root system (rootstock) of another plant. In the second method, a bud is taken from one plant and grown on another. Vascular continuity is eventually established, in both instances, resulting in a genetical composite that functions as a single plant. On one hand, grafting or budding onto resistant rootstocks serves as a principal tool in disease management, but on the other hand, contact between the stock to bud or scion enables the spread of viruses, even without a complete graft union.

Certain parasitic plant species form connections to their hosts, similar to graft junctions, and are able to facilitate the dissemination of virus pathogens. No less than 67 plant viruses and viroids including, but not limited to CMV (*Bromoviridae*), TMV, *Tomato mosaic virus* and *Tobacco rattle virus* (*Virgaviridae*), PVY (*Potyviridae*), *Tomato yellow leaf curl virus*, and *Beet curly top virus* (*Geminiviridae*), along with *Potato spindle tuber viroid* (*Pospiviroidae*) can be transmitted between plants by at least 20 different species of the parasitic plant *Cuscuta* (*Convolvulaceae*) by means of a bridge created between infected and noninfected plant hosts. Parasitic plants produce root-like structures called haustoria which penetrate the host, connect to its vasculature and facilitate the exchange of materials such as water, nutrients, and pathogens between the host and the parasite, and between any plants simultaneously parasitized, even unrelated plant species. *Cuscuta* seems to act in some cases as a passive pipeline between parasitized plants as there is no replication in the parasite. Other viruses, like CMV and *Grapevine leafroll-associated virus 7* (*Closteroviridae*), however, can replicate in *Cuscuta*. Additionally, *Cuscuta* can transmit *Cuscuta*-hosted viruses to the parasitized plant. Finally, parasitism by *Cuscuta* species presumably increases the susceptibility of plants to virus infection.

Zoonosis in the Spread of Viruses

A zoonosis refers to any disease that is naturally transmitted from animals (mostly vertebrates) to humans, or the other way around, and hence represents cross-species transmission of viruses. A vector may be involved, or the virus is transmitted by contact with the infected host or with its direct consumption, or a derived animal product, its fluids or even a vaccine aimed at deterring infection in the intended host. As with all other pathogens, zoonotic spillovers require that the virus overcomes a hierarchical series of barriers in order to establish an infection. The probability of spillover is determined by: (1) amount of available virus (pathogen pressure), (2) dose of exposure, and (3) characteristics (genetic, physiological, and immunological) of the recipient host, that together with (2), determine the severity of the infection. Following cross-species exposure of a recipient host, the within-host barriers determine the likelihood that an infection will establish. Physical barriers include the skin, mucous membranes, mucous, stomach acidity, and absence of virus receptors. Other barriers that may block infection in both infected and neighboring cells include the innate immune response of the host (see

Chapter 10: Host—Virus Interactions: Battles Between Viruses and Their Hosts) and the molecular compatibility between the host and the virus (e.g., lack of host cytoplasmic products required for virus replication and within-host transmission of the virus). If the virus is able to overcome these barriers to replicate and spread in the new host, the outcome of the infection may be the death of the new host and a dead-end spillover infection or sustained human-to-human transmission. Among the zoonoses of viral etiology that affect humans we find rabies, Ebola, Influenza (H1N1), SARS, and Yellow fever, and more recently, Chikungunya and Zika.

Virus Transmission by Vectors

Besides these modes of transmission, some viruses also use a shuttle mechanism involving vectors. A vector is broadly defined as any organism, invertebrate or vertebrate, that functions as a carrier of an infectious agent between organisms. In most cases, acquisition and inoculation of the infectious agent occurs during vector feeding. Common vectors of viruses are found among the arthropods. Those with a piercing-sucking feeding behavior such as mosquitoes (or other blood-feeding dipterans) and ticks are especially significant for vertebrate viruses, and the aphids, whiteflies, thrips, and hoppers for plant viruses. Other animal vectors of viruses include nematodes, bats, rodents, flying foxes, and horses. Species of plasmodiophorids and fungi also vector viruses.

Different modes of virus—vector interactions have been identified by Animal and Plant Virologists. Animal virologists recognize two major categories of virus—vector relationships; viruses are said to be either mechanically transmitted or biologically transmitted by their vectors. Mechanical transmission refers to the nonspecific transmission of viruses by the vector. That is, viruses acquired externally by the vector during normal feeding behavior on an infected organism, are inoculated during the next feed on another organism. On the other hand, biological transmission is characterized by a specific association of a virus with a particular arthropod species or genus and, more importantly, the virus is ingested by the vector and is able to propagate within the vector before transmission to another host can occur. These classifications are still in use today. Plant virologists, however, have developed a more elaborate framework to represent the types of plant virus—vector interactions during transmission. Two major categories of virus—vector relationships have been defined over the years that relate to the acquisition and inoculation periods, retention periods, and latent periods (the time between ingestion of the virus and the ability of the insect to inoculate a host). Namely, circulative and noncirculative. In circulative vector transmission, the virus acquired during vector feeding on an infected host, is ingested, crosses the intestinal barrier and invades the salivary glands. From there, the virus is inoculated into a new host during feeding. If the virus replicates in one or several tissues and vector organs, the interaction is referred to as circulative propagative; if not, it is termed as circulative non-propagative. In noncirculative transmission, the virus binds only to the mouthparts of the vectors (or legs). Neither internalization nor replication in the vector occurs. Noncirculative transmission is further classified as nonpersistent (virus on mouth-parts of vector leading to short term transmission) or semipersistent (movement of the virus to the foregut).

Apart from choosing an appropriate vector, another strategy used by some viruses to guarantee the success of their transmission involves the deliberate manipulation of both the vector and the host. For example, plant viruses may modify the composition of volatiles emitted by infected hosts (CMV and its host *Cucurbita pepo*). This alters the host's perception by the vectors, attracting or repelling vectors. It is reported as well that plant viruses—especially those that circulate through the vector body or infect the vector—modify vector behavior to enhance transmission (*Tomato spotted wilt orthotospovirus* and its thrips vector, *Frankliniella occidentalis)*. The modification of vector behavior by vertebrate-infecting arboviruses has also been investigated and in some instances has been found to be related to changes in saliva protein composition, caused by viral infection of the vector (*Dengue virus* type 2 and its mosquito vector, *Aedes aegypti*).

The sections that follow provide further details on these host–virus–vector interactions. For the sake of brevity, and hopefully clarity, the terminology commonly used by plant virologists is used, including where relevant, the characteristics associated with animal virus-vector transmission. The reader is encouraged to review the articles referred to at the end of the chapter for fruitful and thought provoking discussions on the definition of a vector, the categorization of plant/animal virus–vector interactions and mechanics of vector transmission.

Noncirculative Transmission of Viruses

In noncirculative, nonpersistent stylet-borne mode of transmission, plant virions are retained on the animal's stylet (acrostyle in aphids) during feeding and are released upon feeding (and the secretion of saliva) on another host. Transmission of these viruses results not from mere contamination of virions on aphid stylets, but from specific interactions. In the case of potyviruses, a viral encoded proteinase (HC-Pro) facilitates retention of the virion by acting as a bridge between the **c**oat **p**rotein (CP) and aphid protein(s) associated with the aphid stylet. Aphid transmission of *Cauliflower mosaic virus* (CaMV) is more complex and requires three CaMV-encoded proteins. While noncirculative, nonpersistent transmission of plant viruses is only so far found among viruses transmitted by aphid vectors, several aphid, whitefly, and leafhopper-transmitted viruses show a noncirculative, semipersistent transmission relationship. Here, viruses are also not internalized within the insect vector, but they are retained on chitin-lined areas for longer time periods (Fig. 5.1). *Bemisia tabaci*-transmitted *Lettuce infectious yellows virus* (LIYV; *Closteroviridae*) shows this type of transmission relationship. LIYV requires the CP for its whitefly vector transmission. Virus release is achieved by regurgitation instead of salivation due to the fact that, unlike aphids, the foregut in whiteflies is physically separated from their stylet and salivary ducts.

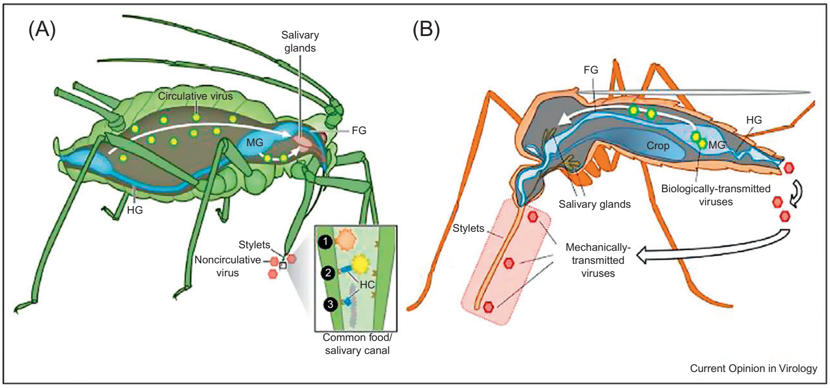

FIGURE 5.1 Different routes of viruses in their arthropod vectors. (A) Pictures the situation for plant viruses where emblematic vectors are aphids, but where other sap-feeding hemipteran insects have similar relationships with the virus they transmit. The gut is represented in *blue* and the salivary glands and salivary duct in *brown*. The white arrows represent the cycle of propagative and circulative viruses (*green hexagons*) within the aphid body, across the gut epithelium to the hemolymph and/or other organs, and ultimately to the salivary glands. While propagative viruses replicate in these organs, circulative viruses are supposed to pass through cellular barriers in a replication-independent manner. Noncirculative viruses appear at their specific attachment sites at the tip of the stylets as *red hexagons*. FG: foregut; MG: midgut; HG: hindgut. The inset at the bottom right represents the common food/salivary canal located at the tip of the aphid maxillary stylets. Noncirculative viruses interact with putative receptors embedded in the cuticle. (1) In the capsid strategy, viruses directly bind putative receptors via a domain of their capsid protein (case 1, for example the genus *Cucumovirus*). (2) In the helper strategy the virus-receptor binding is mediated by additional viral proteins designated *helper components* (HC, *blue*). Best-known cases are the genera Potyvirus (where the HC is designated HC-Pro, case 3) and *Caulimovirus* (where the HC is designated P2, case 2). (B) Pictures the situation for viruses of vertebrates where emblematic vectors are mosquitoes, but where other blood-feeding dipteran insects, or even ticks, have similar relationships with the virus they transmit. The gut is represented in *blue* and the salivary duct and glands in *brown*. The *white* arrow represents the cycle of biologically transmitted viruses (*green hexagons*) within the vector body, across the gut epithelium to the hemolymph and/or other organs, and ultimately to the salivary glands. Biologically transmitted viruses are all believed to replicate in these organs. Mechanically transmitted viruses are thought to be retained with residual blood meal in the mouthparts at undefined locations (*pink* rectangle region of the proboscis). FG, foregut; MG, midgut; HG, hindgut. The *red virions* at the rear of the insect illustrate cases where infectious virus units can be excreted with the feces at (or close to) the feeding sites and may thus contaminate the wounds induced upon vector feeding. Source*: (A) Reproduced from Blanc, S., Gutiérrez, S., 2015. The specifics of vector transmission of arboviruses of vertebrates and plants. Curr. Opin. Virol. 15, 27–33. Available from: https://doi.org/10.1016/j.coviro.2015.07.003.*

This mode of transmission via arthropod vectors is also used by animal viruses and is known as *mechanical transmission*. As indicated above, neither internalization nor replication in the vector occurs. Mechanical transmission of viruses involves the transfer of virions by a vector to a person or animal through direct contact with mouthparts, legs, and/or the body of an arthropod. Unlike plant viruses, however, details on the animal virus proteins involved in these interactions are less known. However, the mechanical transmission of, e.g., *Lumpy skin disease virus* (LSDV, *Poxviridae*) by *Aedes aegypti*, but not by other known similar vectors (*Anopheles stephensi*, *Culex quinquefasciatus*, *Culicoides nubeculosus*, or *Stomoxys calcitrans*) suggest the potential of a complex interaction between the virus and the vector.

Characteristics of the vector–virus relationship for viruses transmitted by soil-inhabiting vectors such as plasmodiophorids, chytrid fungi, and nematodes are less well defined. For the most part, they exhibit features of noncirculative, nonpersistent transmission but also circulative nonpropagative in other cases (see later). Most viruses transmitted by soil-inhabiting organisms are ssRNA(+) viruses, with notable exceptions of members of the genera *Varicosavirus* (*Rhabdoviridae*) and *Ophiovirus* (*Ophioviridae*) with ssRNA (−) genomes. *Beet necrotic yellow vein virus* (*Benyviridae*), transmitted by plasmodiophorids, causes rhizomania disease, characterized by a massive proliferation of lateral roots and rootlets along with severely stunted taproots. *Potato mop-top virus* (*Virgaviridae*), on the other hand, which is also transmitted by plasmodiophorids, causes brown arcs or rings in potato tuber flesh. In the majority of cases, the effects of soilborne virus infection are generally observed on the aerial parts of plants. Plasmodiophorids and fungi, obligate parasites confined to various types of root cells, carry viruses within or on the surface of their zoospores and resting spores. They are transmitted to the plant host, or acquired from it, while the organism is growing within the plant cell. There is no evidence that the viruses can multiply within the vectors. Similarly, nematodes transmit viruses on their stylets, but it also appears that virus can accumulate within the animal. In the latter instances, there is the gradual release of virus during feeding over prolonged periods. *Grapevine fanleaf virus* (GFLV) and *Arabis mosaic virus* (ArMV) are examples of viruses transmitted by two different species of *Xiphinema* nematodes, *X. index* and *X. diversicaudatum.*

Circulative, Nonpropagative Transmission of Viruses

Circulative viruses, by definition, enter the insect body and disseminate to various tissue systems prior to their transmission to plant hosts. This mode of transmission would be referred to as biological transmission in animal virology. In this mode of transmission, circulative, nonpropagative, the virus circulates through the food canal after acquisition, spreads through the midgut, the hindgut, and the hemocoel presumably without replicating in the insect vector. The virus then crosses accessory salivary glands, via the saliva canal, and is transmitted to a new host in the saliva upon feeding. This mode of transmission has been reported for the plant virus families *Geminiviridae*, *Nanoviridae*, and *Luteoviridae* (Fig. 5.1). Aphid transmission of the latter group, luteoviruses, is highly specific. Virus CP is actively involved in the acquisition and transcytosis of virions through the gut to the hemocoel. Another virus protein (the CP read through domain translated from a suppression of termination of the CP gene) allows for the interaction with and passing through membranes of accessory salivary glands of the aphid vector. Phloem host proteins apparently are required for virus uptake and transmission by aphid vectors. Limited examples of this route of transmission have been noted with animal viruses. One example is *Thogoto virus* (*Orthomyxoviridae*) that is vectored by ticks (*Amblyomma variegatum)*. Another interesting example is the LSDV (*Poxviridae*), an economically important disease of cattle that occurs across Africa and in the Middle East. The primary mode of transmission of LSDV is via *Rhipicephalus* tick species. Although the virus invades various tick organs, no evidence has been obtained for replication.

Circulative, Propagative Transmission of Viruses

In other cases, a persistent virus completes a similar cycle within the vector's body, but replicates within the gut, the salivary glands and sometimes other tissues of the insect prior to transmission to new hosts (Fig. 5.1). This is designated as the biological mode of transmission of animal viruses par excellence. In plants viruses, it is the exception more than the rule.

Both phytoarboviruses and animal arboviruses more or less follow the same general pathway of transmission. The virus, present in the plant sap or the animal blood meal after feeding, accumulates at high titers in the midgut cells from which they are subsequently released into the hemocoel. Secondary infections involve other tissues, including reproductive tissues (which allow for the vertical transmission of the virus to the progeny, see later). After infection of salivary glands and release of infectious virions into salivary secretions, the virus is transmitted horizontally to new hosts. Competence for transmission depends on both the virus and the vector(s), but the molecular determinants are not fully known. Evidence indicates that there must be cellular receptors, along with virus ligands, that allow internalization of the virus for its ensuing replication in the vector. Few plant-infecting viruses are transmitted by this mode and belong to the families *Phenuiviridae*, *Reoviridae*, *Rhabdoviridae*, *Tospoviridae*, and *Tymoviridae*. Some members (for instance, *Reoviridae* and *Rhabdoviridae*) are able to infect either animal or plant hosts.

In some virus–vector associations, the virus is believed to directly impact on several components of the vector fitness such as longevity, growth rate, and reproduction, as well as feeding behavior. The response elicited by the virus in host not only influences the insects' fitness, but also virus transmissibility. Additionally, insect competence in transmitting a virus is influenced by its own microbiome.

Vertical Transmission: Parent to Offspring Transmission of Viruses

Vertical transmission refers to generational transmission of viruses from parents to their offspring. HIV-1, e.g., can be acquired *in utero* (via breaks in the placental barrier or transcytosis of cell-associated virus), during delivery (intrapartum), or via breastfeeding. Approximately 20% of viral plant pathogens are known to be seed transmitted. Seed transmission is commonplace in the *Potyviridae*. However, the mechanism by which the virus enters the seed is unknown. There is some evidence in *Pea seed-borne mosaic virus* (*Potyviridae*) that the virus may directly invade the embryo via the suspensor. On the other hand, evidence for the indirect invasion of the embryo via invasion of reproductive meristematic tissue early in plant development has been demonstrated in *Barley stripe mosaic virus* (*Virgaviridae).* At the other extreme are "*vertically transmitted*" viruses that live in symbiotic or commensal associations with their hosts. When temperate bacteriophages achieve a lysogenic state, they are propagated by vertical transmission to the next host generation. That is, transmission to both daughter bacteria is by cell division.

Some viruses utilize both horizontal and vertical routes to transmit and maintain levels in a host population. Bee viruses are one example. Virus transmission in honey bees appears to involve foodborne transmission, venereal transmission, vector-borne transmission, and mother-to-offspring transmission. *Zucchini yellow mosaic virus* (*Potyviridae*) can also be transmitted both horizontally by aphids and vertically by seeds, but the predominant method is by horizontal transmission via aphids in a noncirculative manner. *Tomato yellow leaf curl virus* (*Geminiviridae*) is vectored between susceptible plant hosts by whiteflies (horizontal transmission); the virus is also passed from female vectors to males during copulation (also horizontal transmission) and from females via her eggs to the next generation (vertical/transovarial transmission). Although transmission of mycoviruses is typically achieved by the spread of contaminated mycelia or by hyphal anastomosis, vertical transmission also occurs through mitotic, and sometimes meiotic, spores. Very recently, however, it has been demonstrated that *Sclerotinia gemycircularvirus 1* (*Genomoviridae*) can extracellularly infect its fungal host (*Sclerotinia sclerotiorum*) vectored by the mycophagous fly *Lycoriella ingenua* (Diptera: Sciaridae), whose progeny are also viruliferous. Most probably this is not an isolated case of a mycovirus transmitted by a vector and confirmation of more cases is pending. Understanding transmission dynamics of viruses is particularly important, not only for the identification of key hosts and modes against which interventions could or should be targeted, but also to anticipate potential unintended consequences (positive and negative) that may occur in response to the selective pressures that elimination efforts exert on these systems.

FURTHER READING

Andika, I.B., Kondo, H., Sun, L., 2016. Interplays between soil-borne plant viruses and RNA silencing-mediated antiviral defense in roots. Front. Microbiol. 7, 1458. Available from: https://doi.org/10.3389/fmicb.2016.01458.

Blanc, S., Gutiérrez, S., 2015. The specifics of vector transmission of arboviruses of vertebrates and plants. Curr. Opin. Virol. 15, 27−33. Available from: https://doi.org/10.1016/j.coviro.2015.07.003.

Fenner, F., McAuslan, B.R., Mims, C.A., Sambrook, J., White, D.O., 1974. The Biology of Animal Viruses, second ed. Academic Press, New York, p. 834.

Flint, S.J., Enquist, L.W., Racaniello, V.R., Skalka, A.M., 2003. Principles of Virology: Molecular Biology, Pathogenesis, and Control of Animal Viruses, second ed. ASM Press, Washington, DC, p. 850.

Gibson, K.E., 2014. Viral pathogens in water: occurrence, public health impact, and available control strategies. Curr. Opin. Virol. 4, 50−57. Available from: https://doi.org/10.1016/j.coviro.2013.12.005.

Hull, R., 2001. Matthew's Plant Virology, fourth ed. Academic Press, London, UK, p. 1056.

Lequime, S., Paul, R.E., Lambrechts, L., 2016. Determinants of arboviral vertical transmission in mosquitoes. PLoS Pathog. 12, e1005548. Available from: https://doi.org/10.1371/journal.ppat.1005548.

Mehle, N., Ravnikar, M., 2012. Plant viruses in aqueous environment − survival, water mediated transmission and detection. Water Res. 46, 4902−4917. Available from: https://doi.org/10.1016/j.watres.2012.07.027.

Plowright, R.K., Parrish, C.R., McCallum, H., Hudson, P.J., Ko, A.I., Graham, A.L., et al., 2017. Pathways to zoonotic spillover. Nat. Rev. Microbiol. 15, 502−510. Available from: https://doi.org/10.1038/nrmicro.2017.45.

Wilson, A.J., Morgan, E.R., Booth, M., Norman, R., Perkins, S.E., Hauffe, H.-C., et al., 2017. What is a vector? Philos. Trans. R. Soc. Lond. B Biol. Sci. 372. Available from: https://doi.org/10.1098/rstb.2016.008520160085.

Yeh, Y.-H.-, Gunasekharan, V., Manuelidis, L., 2017. A prokaryotic viral sequence is expressed and conserved in mammalian brain. Proc. Natl. Acad. Sci. 114, 7118−7123. Available from: https://doi.org/10.1073/pnas.1706110114.