

Environmental Engineers and Scientists Have Important Roles to Play in Stemming Outbreaks and Pandemics Caused by Enveloped Viruses

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Environmental engineers and scientists have played pivotal roles in protecting the public from viral illnesses, and continue to do so today. We develop drinking water and municipal wastewater treatment technologies, make discoveries that inform related regulations and policies, and conduct critical research on the presence, persistence, and transport of viruses in the environment. A wide range of impactful research in our field has focused mainly on nonenveloped human enteric viruses such as human noroviruses and enteroviruses. More recently, a number of high-profile outbreaks such as Ebola virus, measles, Zika virus, avian influenzas, SARS, MERS, and the ongoing COVID-19 pandemic have been caused by enveloped viruses. In addition to the RNA or DNA genomes and protective protein capsids that are common to all viruses, enveloped virus structures are also wrapped in bilipid membranes.

The primary mode of transmission for many enveloped viruses is by close contact with infected individuals. Some enveloped viruses, however, are released to the environment by the host and persist on surfaces (i.e., fomites), in the air, or in water, long enough to come into contact with another host for

further onward transmission (i.e., indirect transmission). This includes viruses responsible for influenza and measles. The primary transmission routes for SARS-CoV-2 (the virus that causes COVID-19) are believed to be person-to-person contact and by exposure to large droplets produced from sneezing, coughing or talking, but indirect transmission routes may also play a role.¹ This potential role of the environment in the spread of COVID-19 highlights the multitude of applied research needs that must be addressed to effectively control outbreaks and pandemics as novel enveloped viruses emerge. Environmental engineers and scientists are well positioned to apply their unique skill sets and experience with interdisciplinary research to address these needs.

Virus particles in the air and on fomites are exposed to a range of environmental conditions that influence their persistence. Relative humidity, fomite material, and air temperature can greatly impact enveloped virus inactivation rates.^{2–5} Even the medium in which the virus is suspended can greatly impact persistence.⁶ For example, chlorine-based solutions and hydrogen peroxide gas are effective at inactivating the enveloped virus surrogate Phi6 on fomites,^{7,8} but the presence of blood requires much higher hydrogen peroxide gas doses.⁸ Future mechanistic studies should probe how specific constituents in the matrix, temperature, humidity, and solar radiation each impact inactivation. Furthermore, research quantifying the transfer of enveloped viruses between fomites and skin, and determining effective hand washing and surface sanitizing methods, is needed to inform agent-based risk assessment models.

Viruses have a direct connection to wastewater and drinking water purification when they are excreted in feces or urine (Table 1),⁹ but there is limited data on the concentration of enveloped viruses in feces and urine. The human coronavirus responsible for the 2003 SARS outbreak was able to replicate in the human GI tract and infective particles were detected in stool samples.¹⁰ In fact, aerosolized fecal particles are believed

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Table 1. Mean or Median Viral Loads in the Feces and Urine of Infected Individuals for Three Enveloped Viruses and Two Nonenveloped Viruses^a

virus	enveloped?	urine (gc/mL)	feces (gc/g)	feces (gc/swab)	source
SARS ^b	yes	10 ^{1.3}	10 ^{6.1}	NA	21
cytomegalovirus (CMV) ^c	yes	10 ^{4.5}	NA	NA	22
SARS-CoV-2 ^d	yes	ND	NA	10 ⁵	13
human norovirus GI ^e	no	NA	10 ^{8.5}	NA	23
JC polyomavirus ^f	no	10 ^{4.6}	NA	NA	24

^a“gc” is gene copy. NA = not analyzed in study, ND = analyzed, but not detected in study. ^bSamples from approximately 100 patients with lab-confirmed illness, mean. ^cSamples from 36 children with lab-confirmed illness, median. ^dRectal swab samples from 9 patients with lab-confirmed illness during first week of illness, mean. ^eSamples from 627 patients with gastroenteritis symptoms, median. ^fSamples from 71 health blood donors that tested positive or JC polyomavirus, median.

to have played a major role in spreading the virus at a Hong Kong apartment complex.¹¹ Similarly, SARS-CoV-2 genomic RNA has been detected in feces.^{12,13} Although infective SARS-CoV-2 has not yet been confirmed in stool samples, the SARS-CoV-2 RNA shedding pattern suggests viruses are replicating in the GI tract.¹³ Other human enveloped viruses, such as cytomegalovirus (CMV), are excreted in urine. Research so far on enveloped viruses in wastewater, including coronaviruses, suggest these viruses are inactivated at faster rates than most nonenveloped viruses,^{14–18} that they partition to wastewater solids to a greater extent than nonenveloped viruses,¹⁵ and that wastewater temperature is positively associated with their inactivation rates.^{15,18} In water purification processes, they are generally more susceptible to oxidant disinfectants than nonenveloped viruses.^{19,20} The presence of an envelope does not appear to impact virus susceptibility to ultraviolet C (UVC) light,¹⁵ likely because UVC targets virus genomes and lipid membranes do not shield the genomes from UVC radiation.

What does this mean for the SARS-CoV-2 virus and the ability of our water purification plants to produce safe water? Our drinking water treatment plants, including those used to produce drinking water from wastewater, were designed using microbial risk assessments and process performance data with nonenveloped enteric viruses. Based on the facts that (1) the closely related 2003 SARS was excreted in feces at lower levels than enteric human noroviruses (Table 1), (2) model coronaviruses are inactivated at faster rates in wastewater and other waters than nonenveloped viruses, (3) the enveloped viruses studied to-date are more susceptible to oxidant disinfectants than nonenveloped viruses, and (4) the large single-stranded RNA (ssRNA) genome (~29.8 kb) of SARS-CoV-2 likely renders it more susceptible to UVC inactivation than enteric ssRNA viruses, the multibarrier wastewater and drinking water treatment systems are likely effective in protecting against SARS-CoV-2. Nonetheless, there may still be water-related exposures that need to be considered if infectious SARS-CoV-2 viruses are present in urine or feces. Such exposures may occur in communities that experience combined sewage overflows, that do not have sewage infrastructure, or that use wastewater for irrigation, as well as buildings that have faulty plumbing systems and occupational exposures to wastewater and excrement.

Despite the research outlined above, enveloped viruses are extremely diverse, with a range of genome types, structures, replication cycles, and pathogenicities. For example, of the 158 identified human RNA viruses species as of 2018, 122 species from 11 virus families were enveloped and 36 species from 6 families were nonenveloped.²⁵ Consequently, enveloped viruses likely display a diverse range of environmental behavior, persistence, and fate.²⁶ The limited studies on enveloped-virus fate, transport, and inactivation have focused on only a small fraction of human viruses or their proxies including animal coronaviruses and bacteriophage phi6. Although studies using animal coronaviruses have been valuable for the current COVID-19 outbreak,^{3,15,27} it is essential to consider an expanded set of enveloped viruses that better represent human enveloped virus diversity.

Future studies on enveloped viruses should seek to carefully characterize and even standardize the conditions under which measurements are conducted. Media composition, the purity of virus stock, and when possible, virus concentrations in both gene copies and infective units, should be described. When studying oxidants, the demand of the solution and change in oxidant concentration through the experiment should be provided. When studying radiation (UVC and/or sunlight), attenuation through the experimental solution should be well-characterized incorporated into reported doses. Researchers should include a well-studied surrogate virus in their experiments in addition to the enveloped virus of interest to facilitate cross-study comparisons. We recommend using the nonenveloped bacteriophage MS2 for this purpose, as it is one of the most studied viruses in environmental systems.

Finally, there are emerging research areas in our field that we believe can inform the current COVID-19 outbreak and future novel viral outbreaks. For example, predictive models based on the underlying mechanisms controlling the persistence of enveloped viruses, and other characteristics, may reduce the need to study every virus under every condition.¹⁴ Another promising area of research involves using sewage to monitor virus circulation in communities and detect outbreaks before clinical cases are identified. Recently applied to pathogenic bacteria²⁸ and nonenveloped viruses,²⁹ this will necessitate a better understanding of which enveloped viruses are excreted in urine and feces and at what levels.

SARS-CoV-2 will certainly not be the last novel virus to emerge and seriously threaten global public health. Researchers and funding agencies have a tendency to focus intensely on a specific virus during its outbreak, but then move on to other topics when the outbreak subsides. Given the historical contributions from our field, and the grand challenges that lie ahead,³⁰ environmental science and engineering researchers should take a broader, long-term, and more quantitative approach to understanding viruses that are spread through the environment. Similar to how we approach chemical pollutants in the environment, we should aim to understand and communicate to our colleagues in medicine and public health the specific characteristics that drive transport and inactivation of enveloped viruses in solutions, on surfaces, and in the air. Likewise, we should seek to understand how environmental factors shape possible virus transmission routes. That way, regardless of the identity of the enveloped virus that causes the next major outbreak, we can provide more informed descriptions of its persistence and recommendations on how to mitigate its spread.

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Notes

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