Journal of Food Protection, Vol. 84, No. 8, 2021, Pages 1295–1303
https://doi.org/10.4315/JFP-20-492

General Interest

Exposure Profile of Severe Acute Respiratory Syndrome Coronavirus 2 in Canadian Food Sources

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MS 20-492: Received 23 December 2020/Accepted 26 March 2021/Published Online 26 March 2021

ABSTRACT

A new coronavirus strain known as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has spread worldwide. This virus is the causative agent for coronavirus disease 2019 (COVID-19) and spreads primarily through human-to-human transmission via infected droplets and aerosols generated by infected persons. Although COVID-19 is a respiratory virus, the potential for transmission of SARS-CoV-2 via food is considered theoretically possible and remains a concern for Canadian consumers. We have conducted an exposure assessment of the likelihood of exposure of SARS-CoV-2 in Canadian food sources at the time of consumption. This article describes the exposure routes considered most relevant in the context of food contamination with SARS-CoV-2, including contaminated food of animal origin, other contaminated fresh foods, fomites, and SARS-CoV-2–contaminated feces. The likelihood of foodborne infection of SARS-CoV-2 via the human digestive tract also was considered. Our analysis indicates that there is no evidence that foodborne transmission of SARS-CoV-2 has occurred, and we consider the likelihood of contracting COVID-19 via food and food packaging in Canada as low to remote. Adherence to safe food practices and cleaning procedures would in any case prevent a potential foodborne infection with SARS-CoV-2.

HIGHLIGHTS

- Our analysis shows no evidence of foodborne transmission of SARS-CoV-2.
- The likelihood of contracting COVID-19 via food or food packaging is low to remote.
- Following safe food practices mitigates the likelihood of SARS-CoV-2 transmission.

Key words: COVID-19; Exposure profile; Food; Foodborne transmission; Food packaging; SARS-CoV-2

Coronaviruses are part of a large family of viruses that usually cause mild-to-moderate upper respiratory tract illnesses. There are four common human coronaviruses (229E, NL63, OC43, and HKU1) that cause symptoms similar to the common cold. Conversely, two coronaviruses—severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV)—have been known to cause diseases that are more serious: SARS and MERS. SARS is a viral respiratory illness causing high fever (>38.0°C), headache, overall feeling of discomfort, and body aches *(9)*. Illness associated with this virus was reported from November 2002 to July 2003, resulting in 8,906 cases and 774 deaths *(63)*. MERS is also a viral respiratory illness with symptoms including fever, cough, and shortness of breath *(10)*. After its discovery in 2012, up to January 2020, 2,519 laboratory-confirmed cases of MERS and 866 deaths were reported worldwide to the World Health Organization *(64)*.

In 2019, a new coronavirus strain was identified in China and has since spread worldwide. The virus, known as SARS-CoV-2, causes coronavirus disease 2019 (COVID-19), characterized primarily by fever, cough, shortness of breath, fatigue, loss of appetite, and loss of smell and/or taste *(46)*. Symptoms can appear within a 2- to 14-day period (with a median time of 4 to 5 days from exposure to symptom onset) after exposure to the virus; however, asymptomatic carriers have been reported *(12, 44)*. The COVID-19 outbreak was characterized as a pandemic by the World Health Organization in March 2020, and more than 75 million cases and 1.69 million deaths had been reported worldwide as of December 2020. Concurrently, Canada reported more than 507,000 cases of the disease and 14,200 deaths *(45)*. The Public Health Agency of Canada considers the risk associated with COVID-19 high for Canadians *(45)*.

SARS-CoV-2 is an enveloped RNA virus belonging to the genus *Betacoronavirus,* which also includes SARS-CoV and MERS-CoV. The spread of this virus is primarily through human-to-human transmission via infected droplets and aerosols generated by an infected person, for example,

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when coughing or sneezing. The virus in these droplets and aerosols can be inhaled by others and cause infection by interacting with the receptors in the respiratory system. Infected droplets and aerosols may also be transferred to mucous membranes in the eyes, nose, and mouth from physical contact with surfaces on which these droplets have settled *(40)*. Although COVID-19 is a respiratory disease, concerns have been expressed regarding the potential for transmission of SARS-CoV-2 via food sources. This article discusses the exposure routes considered most relevant in the context of food contamination with SARS-CoV-2 in Canada. Relevant factors for assessing the likelihood of food being contaminated with infectious viral particles capable of causing COVID-19 also are described. The exposure routes considered here are SARS-CoV-2 transmission via (i) contaminated food of animal origin, (ii) other contaminated fresh food products, (iii) fomites, and (iv) SARS-CoV-2–contaminated feces. Finally, the likelihood of foodborne infection of SARS-CoV-2 via the digestive tract is considered.

SARS-COV-2 TRANSMISSION VIA CONTAMINATED FOOD OF ANIMAL ORIGIN

Betacoronaviruses are reported to only infect mammals *(16, 21)*. The current hypothesis is that the primary reservoir for SARS-CoV-2 is bats, based on the virus's genetic similarity to a previously isolated coronavirus from a horseshoe bat sampled in 2013 *(72)*. It is highly probable that the transmission of SARS-CoV-2 from bats to humans was facilitated by a mammalian intermediary (either through increased proximity or as an evolutionary step), which currently remains unidentified.

Some animals are known to be susceptible to SARS-CoV-2 infection, including but not limited to cats, dogs, ferrets, and mink *(11)*. From a food safety perspective, the possibility of SARS-CoV-2 infection in Canadian food-producing animals is the principal concern. Experimental studies involving species of poultry challenged through various routes (intranasal, oral, ocular, and intrachoanal) with SARS-CoV-2 observed no clinical signs of disease, no detectable virus in oropharyngeal and cloacal swabs, no antibodies in the serum, and no detectable virus in tissue samples *(4, 50–52)*. Consequently, it was determined that poultry are not susceptible to infection by SARS-CoV-2. Initially, similar studies in swine challenged intranasally with SARS-CoV-2 were reported *(50, 51)*; however, a study using a higher viral titer revealed that swine may have limited susceptibility to SARS-CoV-2. After infection, several pigs exhibited clinical symptoms such as ocular and nasal discharge, and low levels of viral RNA were detected in nasal washes (in 2 of 16 pigs) and antibodies to SARS-CoV-2 were detected, albeit below protective levels (in 2 of 16 pigs) *(43)*. The authors emphasized that shedding of infectious virus was not observed; no viral RNA was detected in any of the oral, nasal, or rectal swabs, and no infectious viral particles were identified in the nasal washes.

A preliminary study using six experimentally infected calves suggests that cattle may also have limited susceptibility to SARS-CoV-2. Although none of the calves exhibited disease-related symptoms after intranasal inoculation, viral RNA from nasal swabs and seroconversion were detected in two animals *(54)*. The shedding of infectious virus was not assessed in this study, although none of the in-contact animals became infected with the virus (no disease-related symptoms were observed, and no viral RNA was detected in nasal, oral, or rectal swabs).

A rapid qualitative risk assessment conducted by a multijurisdictional Emergency Collective Expert Appraisal Group covered experimental studies related to SARS-CoV-2 in Canadian livestock. The report, published on the Canadian Animal Health Surveillance System Web site, assessed the probability of exposure and infection of Canadian livestock with SARS-CoV-2 from an infected person and considered it "most likely very low" for pigs, ruminants, and horses, and "most likely negligible" for poultry *(7)*. In addition, there are no reported cases of livestock infected with SARS-CoV-2 in Canada *(8, 66)*.

The amount of infectious viral particles present in edible organs and tissues must be high enough to cause a foodborne infection in humans at the time of consumption to be considered a food safety concern. This means that SARS-CoV-2 would need to survive through any processing and storage that the meat or edible organ may undergo before consumption. For pigs, in which limited susceptibility to SARS-CoV-2 was observed, there is no evidence that the virus contaminates edible organs or tissues *(43, 50)*. However, the presence of the virus in edible organs and tissues in cattle was not assessed.

Studies on various coronavirus strains have established that coronaviruses are susceptible to heat inactivation (Table 1). One study of note determined that pasteurization of donor human milk (62°C for 30 min) spiked with 1×10^7 50% tissue culture infectious dose ($TCID_{50}$) of SARS-CoV-2 resulted in undetectable levels of the virus *(55)*. Another study observed different heat inactivation times for SARS-CoV-2 in cell culture media, sera, and nasopharyngeal matrices *(3),* suggesting that the matrix surrounding the virus has a potential effect on SARS-CoV-2 heat susceptibility. Overall, these results suggest that the potential risk of transmission can be mitigated by thoroughly cooking meat and avoiding cross-contamination of raw or undercooked meat with other foods meant to be consumed uncooked or considered ready-to-eat.

SARS-COV-2 TRANSMISSION VIA FRESH AND READY-TO-EAT FOOD PRODUCTS

Fresh and ready-to-eat foods such as meat, produce, and bakery items cannot support the replication of viruses, including SARS-CoV-2; yet, the question of whether the virus can contaminate such foods and be transmitted remains a concern among consumers. Although unlikely to occur, the potential transmission through food would probably be the result of contamination by an infected person.

Preliminary studies on apples, tomatoes, and jalapeño peppers that were experimentally infected to simulate a low-dose aerosol exposure revealed no infectious virus particles at 1 h postexposure at room temperature *(23)*. Another study looked for the presence of viral RNA on produce directly exposed to individuals that tested positive for SARS-CoV-2.

TABLE 1. *Summary of studies investigating SARS-CoV-2 heat inactivation by using infectivity assays*

Initial viral load of SARS-CoV-2	Temp (°C)	Sample media	Time for a decrease in infectivity (1-log reduction)[a]	Time until SARS-CoV-2 is inactivated or undetectable	Reference
6.8 log $TCID_{50}$[b]	4	Virus transport medium	>14 days	>14 days	*15*
	22	Virus transport medium	2 days	14 days	
	37	Virus transport medium	6 h	2 days	
	56	Virus transport medium	$1 < x < 5$ min	30 min	
	70	Virus transport medium	<1 min	5 min	
3.2–5 log $TCID_{50}$	56	Virus transport medium	<30 min	30 min	*2*
	98	Virus transport medium	<2 min	2 min	
7 log $TCID_{50}$	62.5	DMEM 1×[d]	<30 min	>30 min	*55*
	62.5	Human milk	<30 min	<30 min	
6.6 log $TCID_{50}$	56	DMEM 1×	<15 min	30 min	*3*[c]
	56	Pooled donor sera	<5 min	15 min	
	65	DMEM 1×	<15 min	15 min	
	65	Pooled nasopharyngeal samples	<5 min	10 min	
	95	Pooled nasopharyngeal samples	<3 min	3 min	
7.1 log $TCID_{50}$	37	Not specified	$1 < x < 2$ days	>2 days	*61*[c]
	42	Not specified	<1 day	2 days	
	56	Not specified	<15 min	30 min	
	56	Not specified plus 50% human serum	<30 min	30 min	
	60	Not specified	<15 min	15 min	

[a] Results from studies are not directly comparable based on variabilities in initial viral load, time intervals selected, and sample media.
[b] $TCID_{50}$, 50% tissue culture infectious dose.
[c] Publication has not been peer reviewed.
[d] DMEM, Dulbecco's modified Eagle's medium.

The experiment involved placing a tray with seasonal produce in front of COVID-19 patients for 30 min while encouraging conversation and manipulation of the produce by the patients. No viral RNA was detected on the produce at 1 h postexposure at 34°C *(53)*. Although these studies have limitations, they suggest that the transmission of SARS-CoV-2 via fruits and vegetables exposed to COVID-19 patients is unlikely. The likelihood of contamination can be further reduced by following safe food handling practices such as washing produce under running water and hand washing before and after handling food.

When it comes to other fresh food products, such as bakery items, we are unaware of any studies assessing the persistence of SARS-CoV-2 on their surfaces. Out of an abundance of caution, some retail locations have avoided the use of open or uncovered self-service displays and have packaged or covered their products.

SARS-COV-2 TRANSMISSION VIA FOMITES

SARS-CoV-2 transmission is driven primarily via human-to-human contact or prolonged close proximity due to infected secretions generated by an infected person. These infectious droplets can then settle on objects or surfaces (fomites) and potentially lead to infection from touching or handling these surfaces and transferring the virus to mucous membranes in the eyes, nose, or mouth. Studies aiming to determine the shedding timeline of the virus assessed the infectivity of reverse transcription PCR SARS-CoV-2–positive samples (including nasopharyngeal, endotracheal, and sputum) and found infectious virus up to 8 days after symptom onset, with a median $TCID_{50}$/mL of 1,780 (interquartile range, 282 to 8,511) *(6, 62)*. Other studies have shown that SARS-CoV-2 is shed both by asymptomatic and presymptomatic individuals *(29)*. This shedding timeline has important implications for viral transmission, as infected individuals could be unknowingly contagious before and without showing signs of infection. Further research is required to quantify the amount of infectious viral particles shed during activities such as talking, singing, coughing, and sneezing to better characterize the likelihood of SARS-CoV-2 transmission from close contact and from indirect contact via droplets deposited on packing and food contact surfaces.

SARS-CoV-2 on packaging and food contact surfaces. The stability of SARS-CoV-2 on food packaging and food contact surfaces represents a possible food-related transmission route. Several studies investigated the persistence of SARS-CoV-2 on various surfaces (Table 2) and concluded that SARS-CoV-2 remains infectious on smooth surfaces for longer periods than on porous materials. In addition, SARS-CoV-2 persistence on metal surfaces depends on the type of metal inoculated; SARS-CoV-2 remained infectious for several days on stainless steel *(15, 33, 58),* whereas no infectious viruses were identified on copper or aluminum after 4 h *(42, 58)*.

In some studies, organic components were added to the viral inoculum to better represent human respiratory secretions. One comparative study looked at the effects of bovine serum albumin (BSA) on SARS-CoV-2 persistence

TABLE 2. *Summary of studies investigating SARS-CoV-2 persistence on surfaces by using infectivity assays*

Initial viral load	Surface type	Time for a decrease in infectivity (1-log reduction)[a]	Reported persistence	Relative humidity (%) and temp (°C)	Reference
3.6 log $TCID_{50}$[b]	Cardboard	8 h	24 h	40 and 21–23	*58*
	Copper	$2 < x < 4$ h	4 h		
	Stainless steel	$8 < x < 24$ h	3 days		
	Plastic (polypropylene)	$8 < x < 24$ h	3 days		
5.5 log $TCID_{50}$	Printing paper	<30 min	3 h	65 and 22	*15*
	Tissue paper	<30 min	3 h		
	Wood	<30 min	2 days		
	Cloth	<30 min	2 days		
	Glass	$6 < x < 24$ h	$2 < x < 4$ days		
	Stainless steel	24 h	$4 < x < 7$ days		
	Plastic	$3 < x < 6$ h	$4 < x < 7$ days		
	Surgical mask (inner layer)	$6 < x < 24$ h	$4 < x < 7$ days		
	Surgical mask (outer layer)	24 h	>7 days		
4.7 log $TCID_{50}$	Plastic (polystyrene)	2 h	>4 days	45–55 and 19–21	*42*
	Aluminum	<2 h	<4 h		
	Glass	<2 h	1.8 days		
4.7 log $TCID_{50}$ + proteins (BSA)[c]	Plastic (polystyrene)	4 h	>4 days		
	Aluminum	2 h	>4 days		
	Glass	2 h	>4 days		
5.9 log $TCID_{50}$ + soil load (BSA + mucin + tryptone)	Plastic (face shields)	$4 < x < 24$ h	21 days	35–40 and 20	*33*
	Cotton	<1 h	24 h		
	Stainless steel	$4 < x < 24$ h	14 days		
	Gloves (nitrile)	$4 < x < 24$ h	7 days		
	Gloves (chemical resistant)	<1 h	4 days		
	Mask (N-95 and N-100)	$4 < x < 24$ h	21 days		
	Tyvek	$4 < x < 24$ h	14 days		

[a] Results from studies are not directly comparable based on variabilities in initial viral load, time intervals selected, and sample media.
[b] $TCID_{50}$, 50% tissue culture infectious dose.
[c] BSA, bovine serum albumin.

and observed a marked increase in persistence on glass and aluminum when BSA was present as well as a modest increase on plastic surfaces *(42)*. The protective effect of organic components on SARS-CoV-2 was also demonstrated in a study examining viral persistence on several surfaces and personal protective equipment by using a viral inoculum containing BSA, mucin, and tryptone *(33)*.

The results of these studies should be interpreted with caution, because persistence will vary based on parameters such as temperature, humidity, and exposure to light. The surfaces tested in these studies were experimentally inoculated with variable virus titers and may not represent actual contamination by human-secreted droplets and aerosols. In addition, these studies used virus elution as the methodology for virus recovery as opposed to swabbing of surfaces, the latter of which would mimic a more realistic transfer to the person handling the food *(15, 33)*. Ultimately, the amount of infectious SARS-CoV-2 particles that can be transferred via contaminated surfaces has not been quantified at this time. Studies assessing the transfer efficiency of microorganisms have focused primarily on bacteria and phages, which may not accurately represent the transfer efficiency of enveloped viruses such as SARS-CoV-2 *(49)*. Adequate and frequent disinfection protocols are recommended in facilities where food preparation, cooking, and/or handling occur as well as where packaging occurs.

Several studies have confirmed the susceptibility of SARS-CoV-2 to standard disinfectant solutions *(13, 15, 30)* as well as to irradiation with UV light, including UV-C *(27)* and deep UV light–emitting diodes *(31)*. Health Canada maintains a published list of approved hard-surface disinfectants as well as a list of approved hand sanitizers for use against SARS-CoV-2 *(26)*. Similarly, the U.S. Environmental Protection Agency posted "List N: Disinfectants for Coronavirus (COVID-19)" on their Web site *(57),* and the European Chemical Agency posted "COVID-19 List of Disinfectant Active Substances and Products" *(19)*. Although this assessment is focused primarily on SARS-CoV-2, further insight into its characteristics may be extrapolated from studies and reviews comparing its persistence and inactivation with those of other coronaviruses *(1, 22, 32)*.

SARS-CoV-2 in refrigerated and frozen food products. Recent media reports have sparked concerns regarding frozen foods as a vehicle for SARS-CoV-2 transmission across country borders. In June 2020, China reported the presence of SARS-CoV-2 RNA on a cutting board used for imported salmon at a market in Beijing. China has since reported several instances of imported foods testing positive for SARS-CoV-2 *(25)*. It should be noted that SARS-CoV-2 identification is often achieved

using rapid and sensitive molecular methods that detect viral RNA, but do not necessarily give any information on its infectivity. Although specific details of their surveillance data are unknown, positive samples were most frequently linked to packaging of frozen shrimp, seafood, and chicken. Given this information, the postulated transmission route relating to frozen foods is not linked to the ingestion of food, but to its packaging as a fomite.

Refrigeration and freezing temperatures do not inactivate coronaviruses, but rather extend their survival. Several studies assessing the persistence of SARS-CoV-2 at refrigeration temperatures determined that this virus was highly stable at 4°C, with viable viral particles detected after 14 days *(13, 15)*. Another preliminary study (Dai et al. *(17)*) reported that SARS-CoV-2 was infectious for more than 8 days at refrigerated (4°C) temperatures on the surface of fish, followed by a decline in infectivity after 10 days. A rapid decrease in infectivity was observed in fish stored at 25°C after 2 days.

Poultry, fish, crustaceans, and molluscs are not susceptible to infection by SARS-CoV-2 *(4, 5, 50)*. This implies that the viral RNA detected on positive food samples most likely originated from an infected individual somewhere along the processing chain in the facility, before packaging. In fact, food processing facilities have been identified as hot spots for COVID-19 clusters in several countries during this pandemic due to, for example, crowded workplace settings, prolonged close contact with coworkers, and shared transportation and housing *(59, 60)*. Potential opportunities for SARS-CoV-2 contamination of outer food packaging may also extend beyond the processing chain and occur during handling, transport and shipping, and storage.

These occurrences highlight the importance of preventative measures in the food industry where SARS-CoV-2 can spread rapidly due to crowded working conditions. Individuals should not enter workplace premises if they exhibit symptoms of illness or have tested positive for SARS-CoV-2, even in the absence of clinical signs. Employees should be reminded of good hand and respiratory hygiene practices as well as how to properly wear face masks and personal protective equipment when handling, preparing, cooking, and packaging food products. It is also important to regularly disinfect all high-frequency-touch surfaces in workplace facilities and to not neglect surfaces outside of the food preparation area.

SARS-COV-2 TRANSMISSION VIA FECES

Although COVID-19 is a respiratory illness, gastrointestinal symptoms have been reported in a subset of cases. According to the Public Health Agency of Canada, the reported frequency of diarrhea and nausea or vomiting as a result of COVID-19 infection is 5 to 24% and 5 to 19%, respectively *(44)*. Publications investigating the presence of SARS-CoV-2 in human feces have generated data to better assess the possibility of SARS-CoV-2 transmission resulting from fecal shedding.

Multiple studies have detected viral RNA in either anal swabs or stool samples taken from COVID-19 patients *(28, 69, 71)*. A systematic review by Parasa et al. *(41)* indicated that up to 30 to 50% of COVID-19 patients that have tested positive for SARS-CoV-2 RNA in nasopharyngeal swabs or respiratory secretions may have positive fecal swabs for SARS-CoV-2 RNA as well. Conversely, fewer studies have identified infectious SARS-CoV-2 virus in fecal samples by using culture methods *(14, 37)*. Xiao et al. *(69)* also demonstrated the presence of SARS-CoV-2 in gastrointestinal epithelium, including the cytoplasm of gastric, duodenal, and rectum glandular epithelial cells, by using immunofluorescent staining. In vivo studies revealed that new viral particles were being released toward the lumen of the intestines, and subsequent experiments showed residual recombinant SARS-CoV-2 fluorescent reporter virus particles after 24 h in simulated human small intestinal fluid *(70)*. Moreover, virus particle levels significantly decreased after a 1-h exposure to simulated human colonic fluid and continued to decrease for up to 24 h.

Detectable levels of SARS-CoV-2 genetic material in fecal matter have enabled the use of wastewater-based epidemiology and have led numerous researchers worldwide to detect and quantify SARS-CoV-2 RNA in untreated wastewater *(38, 39, 47, 67, 68)*. However, infectious SARS-CoV-2 viral particles have not been detected in any wastewater samples, most likely due to the unfavorable conditions for coronavirus persistence in such an environment *(34, 48)*. Regardless, these studies have generated concerns of possible bioaccumulation of SARS-CoV-2 in bivalve molluscs if wastewater overflow occurs near shellfish-growing areas during heavy rainfalls.

A qualitative risk assessment prepared by the Food Safety Authority of Ireland looked at the risk of contracting COVID-19 via the consumption of bivalve molluscs produced in Ireland *(20)*. The analysis considered factors such as SARS-CoV-2 persistence in wastewater, in aquatic environments, and after sewage treatment as well as the capacity for live bivalve molluscs to bioaccumulate the virus. The report concluded that the probability of consuming bivalve molluscs containing infectious SARS-CoV-2 (accumulated from their environment) was considered very low for raw products and negligible for cooked products, depending on the cooking parameters. Subsequently, these authors considered the risk of contracting COVID-19 from the consumption of such contaminated products to be negligible.

Other food safety concerns stem from the possibility of livestock or irrigation water being exposed to wastewater contaminated with SARS-CoV-2. As stated, food-producing animals are not particularly susceptible to infection by SARS-CoV-2, and concerns of contamination can be addressed by following safe food practices such as cooking meat thoroughly and washing produce under running water.

Taking into account that current studies use molecular-based methods for quantifying levels of SARS-CoV-2 RNA in human feces, further studies are required to quantify the levels of infectious particles shed in human feces before we can determine whether the fecal-to-oral route can be a source of transmission for SARS-CoV-2. According to a World Health Organization interim guidance document

TABLE 3. *Summary of studies investigating SARS-CoV-2 persistence in simulated human digestive fluids by using infectivity assays*

Initial viral load	Simulated human digestive fluids	Time for a decrease in infectivity (1-log reduction)[a]	Time until SARS-CoV-2 is inactivated at 37°C or undetectable	Reference
2.5×10^5 PFU of SARS-CoV-2-mNeonGreen virus	Fasted state simulated gastric fluid (FaSSGF, pH 1.6)	<10 min	10 min	*70*
	Fasted state simulated intestinal fluid (FaSSIF-V2, pH 6.5)	>24 h	>24 h	
	Fasted state simulated colonic fluid (FaSSCoF, pH 7.8)	$1 < x < 24$ h	24 h	
10^5 PFU of SARS-CoV-2	Fasted state simulated gastric fluid (FaSSGF, pH 1.6)	<30 min	30 min	*36*
	Fed-state simulated gastric fluid (FeSSGF, pH 5.0)	>120 min	>120 min	
	Fasted state simulated intestinal fluid (FaSSIF, pH 6.5)	>120 min	>120 min	
	Fed-state simulated intestinal fluid (FeSSIF, pH 5.0), with bile	0 min	0 min	

[a] Results from studies are not directly comparable based on variabilities in initial viral load and time intervals selected.

published in July 2020, "The risk of transmission of SARS-CoV-2 from the faeces of an infected person and the fecal-oral pathway appears to be low" *(65)*. There are currently no reported cases of COVID-19 resulting from fecal-to-oral transmission.

SARS-COV-2 INFECTION VIA THE DIGESTIVE TRACT

SARS-CoV-2 attaches to host cells via interactions between its spike glycoprotein, situated on the virus's outer envelope, and the host cell receptor. Like SARS-CoV, the cellular receptor for SARS-CoV-2 is angiotensin-converting enzyme 2 (ACE2), an enzyme that is present in multiple types of cells, including those in contact with the external environment in the oral and nasal mucosa, nasopharynx, lungs, and small intestines *(24)*.

Studies show that SARS-CoV-2 is capable of infecting human intestinal epithelial cells *(69, 70)*. However; it has yet to be confirmed whether it is the result of ingestion or systemic spread of the virus. One research group focused on the ACE2 receptor and SARS-CoV-2 localization in esophageal, gastric, duodenal, and rectal tissues biopsied from a COVID-19 patient *(69)*. The cytoplasm of the gastrointestinal epithelial cells was positive for ACE2, and the cytoplasm of gastric, duodenal, and rectum glandular epithelial cells was positive for viral nucleocapsid protein. In the esophageal epithelium, which consists mostly of squamous epithelial cells, no viral nucleocapsid protein staining was observed and ACE2 expression was rare. These results indicate that infection via cells in the esophagus is unlikely; however, more research is required to support this hypothesis.

Several researchers have focused on the ability of SARS-CoV-2 to persist in the harsh environment of the human digestive tract, which consists of acidic gastric fluids, high-pH bile, and digestive enzymes. Although virus titers required for oral infectivity in humans remains unknown, one infectivity study using a hamster model showed that a higher SARS-CoV-2 dose (~1,000-fold) was required for oral inoculation versus intranasal inoculation *(36)*. These findings suggest that the environment of the digestive tract may present hurdles to the virus's survival and thus its ability to infect the host.

The human digestive tract generally ranges from a pH of 1 to 3 in the stomach and a pH of 6 to 8 in the intestines. The authors of two studies independently determined that SARS-CoV-2 was stable in a wide range of pHs (3 to 10), but lost infectivity within 1 day when nearing pH extremes (pH 2 to 3 and pH 11 to 12) *(13, 15)*. Several studies also assessed the stability of SARS-CoV-2 in simulated digestive fluids to represent human digestive conditions more accurately (Table 3). Results from these studies appear to indicate that SARS-CoV-2 can be readily inactivated by fasted state simulated gastric fluid or bile of healthy, middle-aged individuals. In addition, Larsen and Wigginton *(35)* have stated that released SARS-CoV-2 viruses are rapidly inactivated in the gastrointestinal tract fluid and appear to be noninfective when excreted. However, further research is required to characterize SARS-CoV-2 stability in

a variety of foods after exposure to gastric fluids at various pH and bile levels.

Many researchers have postulated scenarios in which the likelihood of infection from SARS-CoV-2 via the digestive tract is increased, all of which describe a decrease in stomach acidity. For example, individuals taking medication to reduce gastric acidity, such as proton pump inhibitors, have increased gastric pH levels, and this may create a more favorable environment for SARS-CoV-2 *(13, 36, 56)*. Similarly, some individuals may be in a state of hypochlorhydria (low stomach acid) as a result of aging or a medical condition (e.g., atrophic gastritis, *Helicobacter pylori* infection) *(18, 56)*. Consumption of certain foods may also influence SARS-CoV-2 survival in the digestive tract by increasing stomach pH levels or by providing a protective matrix.

CONCLUSIONS

In order for foodborne transmission of SARS-CoV-2 to occur, several steps are required: (i) the food needs to be contaminated with the virus, either at source or during processing; (ii) the virus needs to be able to survive during transport, processing, and retail; (iii) the virus has to remain infectious during storage and through any preparation steps before consumption, such as peeling, washing, and/or cooking; and (iv) the virus needs to be present in high enough levels and able to infect the consumer after ingestion of the contaminated food. Further research regarding the persistence of SARS-CoV-2 on food surfaces, the amount of infectious viral particles that can be transferred via contaminated surfaces (including food), and the infectious dose for oral infectivity would provide valuable insight into the likelihood of SARS-CoV-2 transmission via food sources.

Based on the analysis of the most recent examination of scientific literature, Health Canada's Food Directorate has conducted an exposure profile of the likelihood of SARS-CoV-2 in Canadian food sources at the time of consumption. We conclude that there is no indication for foodborne transmission of SARS-CoV-2 in Canadian food sources, and Health Canada considers the likelihood of contracting COVID-19 via food and food packaging in Canada to be low to remote.

We recommend that consumers continue to follow the public health advice in their communities and continue following safe food handling and cooking practices. The likelihood of any potential SARS-CoV-2 transmission via food sources can be further minimized by following proper hand and respiratory hygiene practices. Adequate hand washing for at least 20 s with soap and warm water is recommended before and after touching foods (raw or cooked) and their packaging. In addition, adherence to safe food practices and disinfection procedures, including the thorough cooking of food, will prevent cross-contamination and inactivate SARS-CoV-2.

ACKNOWLEDGMENTS

We acknowledge the contributions of Dr. James Strong (Senior Research Scientist at the National Microbiology Laboratory) and Dr. Moez Sanaa (Senior Researcher at the Agence Nationale de Sécurité Sanitaire de l'Alimentation, de l'Environnement et du Travail) for their valuable insights and participation in the scientific discussions regarding this article. In addition, we thank Captain William Burkhardt III, PhD (U.S. Food and Drug Administration), Dr. Joanne Hewitt (New Zealand Institute of Environmental Science and Research), and Dr. Jeff Farber (University of Guelph, Canada) for their valuable insights in shaping this article.

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