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Decontamination of SARS-CoV-2 from cold-chain food packaging provides no marginal benefit in risk reduction to food workers

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ABSTRACT

Countries continue to debate the need for decontamination of cold-chain food packaging to reduce possible severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) fomite transmission among frontline workers. While laboratory-based studies demonstrate persistence of SARS-CoV-2 on surfaces, the likelihood of fomite-mediated transmission under real-life conditions is uncertain. Using a quantitative microbial risk assessment model of a frozen food packaging facility, we simulated 1) SARS-CoV-2 fomite-mediated infection risks following worker exposure to contaminated plastic packaging; and 2) reductions in these risks from masking, handwashing, and vaccination. In a frozen food facility without interventions, SARS-CoV-2 infection risk to a susceptible worker from contact with contaminated packaging was 1.5×10^{-3} per 1h-period (5th – 95th percentile: 9.2×10^{-6}, 1.2×10^{-2}). Standard food industry infection control interventions, handwashing and masking, reduced risk (99.4%) to 8.5×10^{-6} risk per 1h-period (5th – 95th percentile: 2.8×10^{-8}, 6.6×10^{-5}). Vaccination of the susceptible worker (two doses Pfizer/Moderna, vaccine effectiveness: 86–99%) with handwashing and masking reduced risk to 5.2×10^{-7} risk per 1h-period (5th – 95th percentile: 1.8×10^{-9}, 5.4×10^{-6}). Simulating increased transmissibility of current and future variants (Delta, Omicron), (2-, 10-fold viral shedding) among a fully vaccinated workforce, handwashing and masking continued to mitigate risk (1.4×10^{-6} - 8.8×10^{-6} risk per 1h-period). Additional decontamination of frozen food plastic packaging reduced infection risks to 1.2×10^{-8} risk per 1h-period (5th – 95th percentile: 1.9×10^{-11}, 9.5×10^{-8}). Given that standard infection control interventions reduced risks well below 1×10^{-4} (World Health Organization water quality risk thresholds), additional packaging decontamination suggest no marginal benefit in risk reduction. Consequences of this decontamination may include increased chemical exposures to workers, food quality and hazard risks to consumers, and unnecessary added costs to governments and the global food industry.

1. Introduction

According to the World Health Organization (WHO, 2020a) and the United States (U.S.) Centers for Disease Control and Prevention (CDC, 2021), severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) fomite-mediated transmission is rare (Lewis, 2021; Mondelli et al., 2021), compared to the predominant aerosol and droplet transmission modes (Meyerowitz et al., 2021). Fomites (e.g., surfaces) can become contaminated from an infected individual by: 1) shedding onto hands which then touch a surface; or 2) expelled respiratory particles (from coughing, speaking) (Bourouiba, 2020; Morawska et al., 2009) which then fall to a surface (Fernstrom & Goldblatt, 2013). An individual may then transfer infectious particles from a contaminated surface to their facial mucosa (Bueckert et al., 2020). However, definitive epidemiological evidence of fomite transmission is lacking. Few case reports implicate fomites as a possible SAR-CoV-2 source (Cai et al., 2020; Xie et al., 2020) of which, asymptomatic aerosol transmission could not be eliminated as an alternative transmission mode.

Despite these sparse data, a report of the isolation of infectious SARS-CoV-2 from imported frozen cod packaging in Qingdao, China (Liu et al., 2020) has raised alarm for fomites to serve as vectors for seeding SARS-CoV-2 into areas with controlled transmission (Ji et al., 2021). Further, laboratory studies suggest prolonged SARS-CoV-2 infectivity (days to weeks) (Riddell et al., 2020) on surfaces (Pastorino et al., 2020;

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van Doremalen et al., 2020) and low temperatures and humidity (common in cold-chain conditions) were associated with virus stability (months or longer) (Aboubakr et al., 2021). SARS-CoV-2 viral RNA has been detected on surfaces in playgrounds, retail stores (Harvey et al., 2021; Singh et al., 2021), and healthcare settings (Jiang et al., 2020; Ong et al., 2020). However, the relationship between detectable viral RNA and infectious virus is tenuous (estimated 4:1 ratio viral RNA copies to infectious virus) (Sender et al., 2021). Of 63 studies testing for SARS-CoV-2 RNA on surfaces, only 13 attempted to isolate infectious virus. Of these, viable SARS-CoV-2 virus was identified in only four instances: frozen cod packaging (Liu et al., 2020), a nightstand of an infected case (Marcenac et al., 2021), an isolation room of patients undergoing mechanical ventilation (Ahn et al., 2020), and on a windowsill of a patient's quarantine unit (Santarpia et al., 2020). In a cold-chain food setting, evidence is lacking on the frequency of SARS-CoV-2 contamination on packaging and the infection risks to workers.

To prevent potential SARS-CoV-2 outbreaks associated with imported food products, China implemented testing and disinfection (e.g., wet wiping of plastic packaging (Ji et al., 2021; Malenovska, 2020)) on all imported cold-chain (temperature-controlled transport and storage) products and packaging. However, there is no definitive evidence of SARS-CoV-2 fomite transmission from contact with contaminated food or packaging (Goldman, 2021), suggesting that these decontamination measures may be extreme (Goldman, 2020; Lewis, 2021) and may lead to unintended chemical exposures for workers and consumers (Dewey et al., 2021). Thus, using a quantitative microbial risk assessment (QMRA) model, our goals were to simulate in a frozen food packaging facility: 1) SARS-CoV-2 fomite-mediated infection risks following worker exposure to contaminated plastic packaging; and 2) reductions in these risks from masking, handwashing, vaccination, and additional packaging decontamination.

2. Materials and methods

2.1. Model overview

We applied the validated QMRA model of Sobolik et al. (2022) to simulate contamination of plastic packaging (cartons, plastic-wrapped palletized cartons) with SARS-CoV-2 respiratory particles from two coughing, infected workers. We simulated the SARS-CoV-2 exposure doses and infection risks to a susceptible worker in a receiving warehouse resulting exclusively from fomite transmission.

2.2. Model structure

The model initiates with two infected workers in a representative frozen food manufacturing facility (Fig. 1). In this facility, products (e.g., potatoes, blueberries, peas etc.) are placed within a blast tunnel quick freezer (−18 °C), where they are frozen along its conveyor belt. Once frozen, products exit the tunnel freezer and fall into individual plastic-lined cartons. We assumed the first worker was within ≤3 feet of the cartons, with an estimated 144–216 cartons (dimensions: [0.38m × 0.28m x 0.15m] or [0.38m × 0.30m x 0.23m]) processed per hour. The

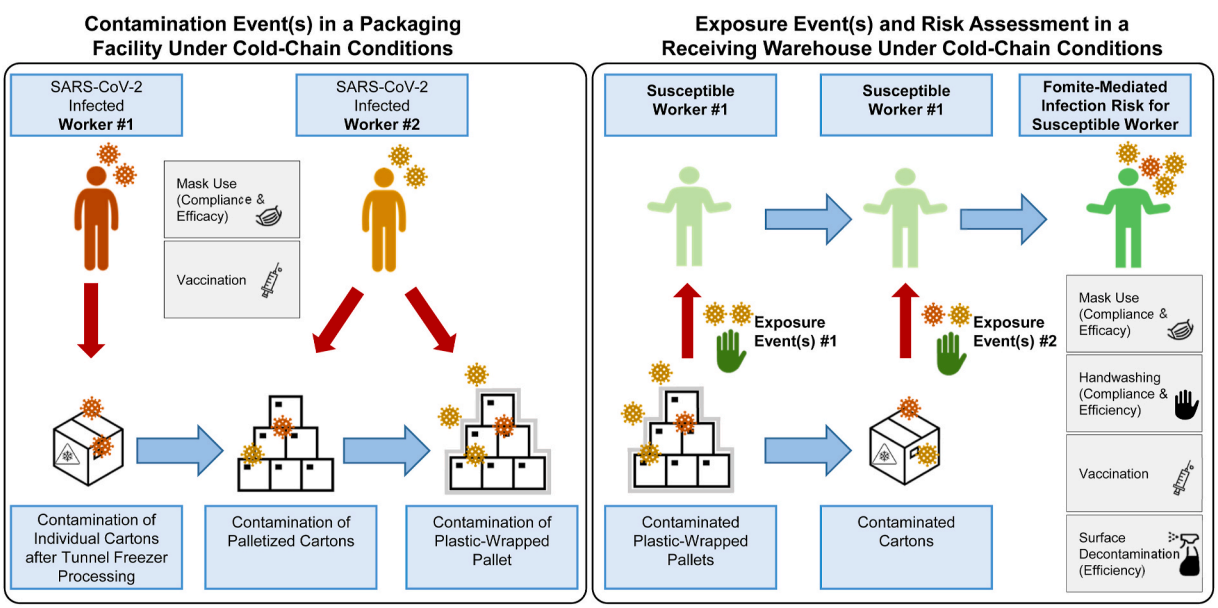

Fig. 1. Conceptual framework for fomite-mediated SARS-CoV-2 transmission involving exposure of a susceptible worker to individual plastic cartons, palletized cartons, and plastic wrap in a receiving warehouse under cold-chain conditions. This schematic depicts a representative frozen food manufacturing facility, initiating with two infected workers (left panel). Up to 10 contamination events per infected worker (0–10 coughs) can occur at three stages in the packaging pipeline (See Materials and methods): 1) contamination of the top-face of individual plastic cartons (144–216 individual cartons processed per hour) via respiratory droplet and aerosol fallout from the first infected worker (orange in schematic) while closing cartons filled with frozen product at the end of the tunnel freezer; 2) contamination of cartons via respiratory particle spray (droplets and aerosols) as cartons are placed (manually or via automation) on a pallet by the second infected worker (yellow in schematic); and 3) contamination of the plastic-wrapped palletized cartons by respiratory particle spray (droplet and aerosol) from the second infected worker (yellow in schematic). Four pallets, each containing approximately 36–54 individual plastic cartons, are processed per hour. All workers were assumed to be continuously wearing gloves (glove changes were not simulated) and the model assumed there was no indirect transfer of virus from the infected workers' hands to the plastic fomites along the packaging pipeline. Given current estimates of limited to no SARS-CoV-2 viral decay at and below 4 °C, the model assumed no loss in viral infectivity during the duration of cold-chain storage and shipment (−20 °C) of individual and plastic-wrapped palletized cartons prior to their handling and during unloading by a susceptible worker in a receiving warehouse. Infection risks resulting exclusively from fomite transmission were simulated as contacts between the susceptible worker's fingers and palms (of both hands) and the fomite surface (accounting for the surface area of the hand relative to the fomite surface); virus transfer from fomite to hands; and virus transfer from fingertips to facial mucous membranes (accounting for the surface area of the fingers relative to the combined surface area of the eyes, nose, and mouth). Gray boxes indicate infection control interventions implemented for the infected (masking, vaccination) and susceptible (handwashing, masking, vaccination) workers. In the scenarios with additional plastic surface decontamination, this was simulated prior to the susceptible worker contacting the fomites.

second infected worker transferred these cartons onto a wooden pallet (36–54 cartons/pallet), either manually or by automation, and then plastic-wrapped the pallet (four pallets processed/hour). We assumed infected workers coughed SARS-CoV-2-laden aerosol (<50 μm) and droplet (50–750 μm) respiratory particles when in close proximity to the cartons, during palletization, and plastic-wrap processing. Plastic-wrapped, palletized cartons were stored and transported under cold-chain conditions (−20 °C) to a receiving warehouse where a susceptible worker was exposed to the virus exclusively via direct contact with contaminated plastic wrap and/or surface-contaminated cartons during manual unpacking of the pallets. Ambient air temperature outside of the tunnel freezer in the frozen food facility and in the receiving warehouse was assumed to be 4 °C. Workers were assumed to wear gloves continuously (glove changes not simulated) following current Good Manufacturing Practices (FDA, 2016).

The two model outcomes included: 1) the SARS-CoV-2 infection risks from fomite-mediated exposures to the cartons and plastic-wrapped pallets following a 1-hour period; and 2) the relative reduction in SARS-CoV-2 infection risk from masking, handwashing, vaccination, and package surface decontamination. The model was developed in R (v.4.0.3; R Development Core Team; Vienna, Austria) using the "mc2d" package (Pouillot & Delignette-Muller, 2010). We conducted 10,000 Monte Carlo iterations for each scenario and reported the median infection risk with 5th and 95th percentiles. Additional details on model assumptions, vetting, and stability, and variability/uncertainty analyses are in *Appendix A Supplementary data*.

2.3. Data sources

Model parameters were derived from the peer-reviewed literature (Table 1) and included: (i) viral shedding through cough events; (ii) fomite-mediated transmission parameters; (iii) dose-response parameters for SARS-CoV-2 infection risk; and (iv) risk mitigation interventions.

2.4. Fomite-mediated transmission modeling

SARS-CoV-2 contamination of the plastic cartons was calculated using the combined aerosol and droplet particle fallout, $Fall_{t,a}$ (infectious virus) and $Fall_t$ (infectious virus/m^3) by the first infected, coughing worker as described (Sobolik et al., 2022). Contamination of the palletized cartons and plastic-wrapped pallets was calculated using the combined aerosol and droplet particle spray, $C_{t,aerosol}$ (plaque-forming unit [PFU]/m^3) and $C_{t,droplet}$ (PFU/m^3), expelled from coughs by the second infected worker as described (Sobolik et al., 2022) with the resulting fomite surface viral concentration:

Cartons, $Fomite_{cartons}$, (PFU/m^2):

$$Fomite_{cartons} = \frac{Fall_{t,\ a} \cdot H_{sa}}{SA_{\ contamcompcart} \cdot SA_{\ compcart}} + \frac{Fall_t \cdot f_V \cdot H_{sa}}{SA_{\ contamcompcart} \cdot SA_{\ compcart}}$$

Plastic-wrapped pallets, $Fomite_{plasticwrap}$, (PFU/m^2):

$$Fomite_{plasticwrap} = \frac{C_{t,\ aerosol} \cdot f_V \cdot H_{sa}}{SA_{\ contamcomppw} \cdot SA_{\ comppw}} + \frac{C_{t,\ droplet} \cdot f_V \cdot H_{sa}}{SA_{\ contamcomppw} \cdot SA_{\ comppw}}$$

where f_V was the facility air volume (m^3), H_{sa} was the surface area of the susceptible worker's hand touching the fomite surface (m^2), $SA_{contamcompcart}$ was the cross-sectional area of the composite contaminated individual cartons (m^2), $SA_{compcart}$ was the cross-sectional area of the composite individual cartons (m^2), $SA_{contamcomppw}$ was the cross-sectional area of the contaminated plastic wrap (m^2), and SA_{comppw} was the cross-sectional area of the composite total plastic wrap (m^2). When calculating contamination of the packaging, aerosol particles (<50 μm) were assumed to be homogenously mixed throughout the facility, consistent with the QMRA modeling of Azimi et al. (2021); Nicas et al. (2005); Zhang et al. (2021). The droplet proportion (50–750 μm) capable of reaching the cartons (droplet fallout) or plastic wrap (droplet spray) within 0–3 feet distancing was derived from previous models (Bourouiba et al., 2014).

The SARS-CoV-2 concentration transferred to a hand, $C_{hand,carton}$ (PFU/h), following contact with the cartons, $Fomite_{cartons}$ (PFU/m^2), was calculated as per (Nicas & Best, 2008).

$$C_{hand,\ carton}(t) = \frac{H_{surface,\ carton} \cdot Fomite_{cartons} \cdot TE_{fh}}{\lambda_{\ v,hand}} \cdot \left[1 - exp\left(-\lambda_{\ v,hand} \cdot t\right)\right]$$

$H_{surface,carton}$ was the contact frequency between the hand and the cartons (contacts/min), $Fomite_{cartons}$ was the viral concentration on the cartons (PFU/m^2) at time t, TE_{fh} was the proportion of virus transferred from fomite to hand, and $\lambda_{v,hand}$ was the SARS-CoV-2 viral decay on the hand. The same approach was taken for calculating the SARS-CoV-2 concentration transferred to a hand, $C_{hand,pw}$ (PFU/h), following contact with the plastic wrap (*Appendix A Supplementary data*).

2.5. Risk assessment

The fomite-mediated dose ($D_{fomite,i}$) to the susceptible worker following contact while unloading the palletized cartons was calculated from the viral contamination on the hand ($C_{hand,i}$) at time t, where i = carton or plastic wrap, the frequency of hand-to-face contacts (H_{face}), the surface area of the hands (H_{sa}), the surface area ratio of fingers (F_{sa}) to face ($Face_{sa}$), the fraction of pathogens transferred from hand-to-face (TE_{hm}), and the exposure duration (t).

$$D_{fomite,\ i}(t) = \frac{H_{face} \cdot H_{sa} \cdot F_{sa} \cdot C_{hand,i}(t) \cdot TE_{hm} \cdot t}{Face_{sa}}$$

The total viral dose, $D_{fomite,total}$ (PFU), at time t, was:

$$D_{fomite,\ total} = D_{fomite,carton} + D_{fomite,plasticwrap}$$

The probability of SARS-CoV-2 infection to the susceptible worker was calculated using $D_{fomite,total}$ (*Appendix A Supplementary data*).

2.6. Evaluating infection control interventions

Standard infection control interventions were selected based on current industry (FAO, 2012; FDA, 2015) and coronavirus disease 2019 (COVID-19) prevention practices (FDA, 2020; WHO, 2020b). These interventions included masking (surgical), hourly handwashing of ungloved hands (2 $\log_{10}$ virus removal) (Grove et al., 2015), and vaccination (two doses of Pfizer/Moderna) of: 1) only the susceptible worker in the receiving warehouse; and 2) all workers, and assuming breakthrough infections among vaccinated workers (*Appendix A Supplementary data*). To handwashing and masking, we simulated the added effect of surface decontamination (3 $\log_{10}$ virus removal) (EPA, 2020; Malenovska, 2020) applied directly to plastic packaging (cartons, plastic wrap) as described (Ji et al., 2021). As there are no infection risk targets for food manufacturing workers, we applied the targets of 1.0×10^{-4} and 1.0×10^{-6} used by Ryan et al. (2014); Wilson et al. (2021).

2.7. Data availability

Model code developed and used in this study is available to readers through GitHub at the following DOI: https://doi.org/10.5281/zenodo.5904275.

3. Results and discussion

3.1. SARS-CoV-2 fomite-mediated infection risks to unvaccinated workers

Assuming no SARS-CoV-2 immunity from vaccination or prior infection, the risk of fomite-mediated transmission without standard infection control interventions was 1.5×10^{-3} per 1h-period (5th – 95th percentile: 9.2×10^{-6}, 1.2×10^{-2}) (Fig. 2A). This is consistent with

Table 1
Model parameter inputs and distributions.

Parameter	Units	Description	Distribution	Input Values	Type of Variability/ Uncertainty	Citations
	Viral Shedding					
$Log_{10}(C_{virus})$	PFU/mL	Concentration of virus in saliva 100X increased viral shedding 10X increased viral shedding 2X increased viral shedding	Triangular	6.8 (6.1, 7.4) 8.8 (8.1, 9.4) 7.8 (7.1, 8.4) 7.1 (6.4, 7.7)	Variability and parameter uncertainty	(To et al., 2020; Wolfel et al., 2020)
$V_{F,c}$	mL/Cough	Fraction of volume associated with aerosols (2–45 μm)	Triangular	2.3×10^{-6} (1.4×10^{-6}, 2.6×10^{-6})	Variability and parameter uncertainty	Chao et al. (2009)
$V_{F,c}$	mL/Cough	Fraction of volume associated with droplets (50–60 μm)	Triangular	6.0×10^{-6} (3.5×10^{-6}, 6.7×10^{-6})	Variability and parameter uncertainty	Chao et al. (2009)
$V_{F,c}$	mL/Cough	Fraction of volume associated with droplets (60–100 μm)	Triangular	4.9×10^{-6} (1.1×10^{-6}, 8.4×10^{-6})	Variability and parameter uncertainty	Chao et al. (2009)
$V_{F,c}$	mL/Cough	Fraction of volume associated with droplets (100–750 μm)	Triangular	6.8×10^{-3} (4.0×10^{-3}, 7.6×10^{-3})	Variability and parameter uncertainty	Chao et al. (2009)
F_C	Cough/h	Number of coughs per hour	Empirical	1/11 equal probability (0, 10)	Variability and parameter uncertainty	(Adhikari et al., 2019; Loudon & Roberts, 1967)
λ_{virus}	Hour	Aerosol viral decay of SARS-CoV-2 at 40% relative humidity, 38 °F	Point value	0	Fixed parameter	(DHS, 2021a)
pp	Probability	Probability respiratory particles will remain in the air as respiratory spray between 0 and 1m distancing	Uniform	50–60 μm: 1m: 0.82; 60–100 μm: 1m: 0.44; >100 μm: 1m: 0.04	Assumption uncertainty	Bourouiba et al. (2014)
$pp_{droplets}$	Probability	Probability respiratory particles (>100 μm) will remain in the air as respiratory spray between 0 and 1m distancing	Uniform	(0.01, 0.22)	Assumption uncertainty	Bourouiba et al. (2014)
$pp_{falldroplets}$	Probability	Probability respiratory particles (>100 μm) will settle to the fomite surfaces between 0 and 1m distancing	Uniform	(0.07, 0.78)	Assumption uncertainty	Bourouiba et al. (2014)
	Risk Mitigation Interventions[1]					
S_{mask}	Log reduction	Source protection surgical mask efficacy	Uniform	(0.39, 0.57)	Variability	(Lindsley et al., 2021; Maurer et al., 2021; Ueki et al., 2020)
RS_{mask}	Percent reduction	Recipient surgical mask efficacy	Uniform	(0.37, 0.998)	Variability	(Lindsley et al., 2021; Maurer et al., 2021; Ueki et al., 2020)
SD_{eff}	Log reduction	Plastic fomite surface decontamination efficiency	Point value	3 Log_{10} virus	Fixed parameter	(EPA, 2020; Malenovska, 2020)
HW_{eff}	Log reduction	Handwashing efficiency	Point value	2 Log_{10} virus	Fixed parameter	(Grove et al., 2006; Liu et al., 2010)
HW_{freq}	Handwashing/ h	Frequency of handwashing per hour	Point value	1.0	Fixed parameter	Expert elicitation
R_{air}	Air changes/h	Frequency of room air changes per hour (ACH)	Point value	2.0	Fixed parameter	Expert elicitation
$VE_{optimal}$	Percent reduction	Vaccine effectiveness (VE)	Uniform	(0.86, 0.99)	Variability	(Andrejko et al., 2021; Pawlowski et al., 2021; Swift et al., 2021)
$VE_{reduced}$	Percent reduction	Vaccine effectiveness (VE)	Uniform	(0.64, 0.80)	Variability	(Khan & Mahmud, 2021; Moustsen-Helms et al., 2021)
VET	Percent reduction	Vaccine effectiveness against transmission (VET)	Triangular	0.89 (0.82, 0.95)	Variability	Prunas et al. (2021)
	Fomite-Mediated Transmission					
$SA_{carton.top}$	m^2	Surface area of top of individual plastic carton	Uniform	(0.106, 0.116)	Variability and parameter uncertainty	Assumed
SA_{carton}	m^2	Surface area of a single individual plastic carton	Uniform	(0.41, 0.54)	Variability and parameter uncertainty	Assumed
Cartons	Cartons/h	Number of individual plastic cartons processed per h	Uniform	(144, 216)	Variability and parameter uncertainty	Assumed
Pallets	Pallets/h	Number of pallets processed per h	Point value	4.0	Fixed parameter	Assumed
$SA_{plasticwrap.side}$	m^2	Surface area of a single side of plastic wrapped pallet	Uniform	(4.20, 6.97)	Variability and parameter uncertainty	Assumed
$SA_{plasticwrap}$	m^2	Surface area of entire plastic wrapped pallet	Uniform	(25.2, 41.8)		Assumed

(*continued on next page*)

Table 1 (*continued*)

Parameter	Units	Description	Distribution	Input Values	Type of Variability/ Uncertainty	Citations
					Variability and parameter uncertainty	
$Fingers_{sa}$	m^2	Surface area of three finger tips touching the surface	Point value	0.00042	Fixed parameter	Bouwknegt et al. (2015)
H_{sa}	m^2	Area of two hands (palms only)	Point value	0.049	Fixed parameter	Bouwknegt et al. (2015)
decay.time	Days	Transport time between the frozen food manufacturing facility and the receiving warehouse (days)	Uniform	(30, 90)	Variability	Assumed
F_{decay}	$Days^{-1}$	Viral decay rate (PFU per day)	Uniform	(0.14, 0.22)	Variability	Kwon et al. (2021)
TE_{fh}	PFU	Viral transfer fraction from fomite to hand with relative humidity (15–32%); acrylic surface [2]	Triangular	0.217 (0.067, 0.367)	Variability and parameter uncertainty	Lopez et al. (2013)
TE_{hf}	PFU	Viral transfer fraction from hand to fomite surface	Point value	0.025	Fixed parameter	(Bean et al., 1982; Greene et al., 2015; Nicas & Jones, 2009; Rusin et al., 2002)
TE_{hm}	PFU	Viral transfer fraction from hand to face	Triangular	0.200 (0.137, 0.263)	Variability and parameter uncertainty	Lopez et al. (2013)
freq.hs	Contacts/min	Frequency of contacts from hand to individual plastic cartons	Point value	Cartons/60	Fixed parameter	Assumed
freq.hs.pw	Contacts/min	Frequency of contacts from hand to plastic wrap	Uniform	(4/60, 20/60)	Variability and parameter uncertainty	Assumed
freq.hf	Contacts/min	Frequency of contacts from hand to face	Point value	0.80	Variability and parameter uncertainty	Nicas and Best (2008)
$Hand_{decay}$	Minutes	Viral decay rate on hands (PFU/min)	Uniform	(0.92, 1.47)	Variability	Nicas and Jones (2009)
eyes.sa	m^2	Surface area of mucous membranes—eyes	Uniform	(1×10^{-5}, 2×10^{-4})	Variability	Wilson et al. (2018)
nose.sa	m^2	Surface area of mucous membranes—nose	Uniform	(1×10^{-5}, 1×10^{-3})	Variability	Wilson et al. (2018)
mouth.sa	m^2	Surface area of mucous membranes—mouth	Uniform	(1×10^{-4}, 4.1×10^{-3})	Variability	Wilson et al. (2018)
	SARS-CoV-2 Dose and Risk Characterization					
$Ratio_{infectious}$	No units	Infectious to non-infectious ratio	Point value	1:100	Fixed parameter	Pitol and Julian (2021)
k_{risk}	PFU^{-1}	Dose-response parameter	Point value	0.00680	Fixed parameter	Pitol and Julian (2021)

Note. [1]All interventions were assumed to be implemented with 100% compliance. [2]Fomite-to-hand transfer rate derived from laboratory studies with bacteriophage MS2.

(Wilson et al., 2021), who simulated an infection risk of approximately 1.0×10^{-3} resulting from a single contact with a high SARS-CoV-2 bioburden (1 to 10,000 genome copies/cm^2)-contaminated fomite with no disinfection. Similarly, comparable fomite-mediated risks on the order of 1 in 10,000 were reported by Pitol & Julian (2021) and Harvey et al. (2021) associated with contacting community fomites (playgrounds, crosswalk buttons etc.). In contrast, higher relative risks associated with SARS-CoV-2 fomite transmission (range: 2×10^{-2} – 3.2×10^{-1} infection risks) were reported in modeling studies of child daycare centers (Kraay et al., 2021) and hospitals (Jones, 2020; Mizukoshi et al., 2021). SARS-CoV-2 bioburden on environment-specific fomites (Wilson et al., 2021) and fomite-specific contact frequencies likely explain these differences in risk estimates. These data confirm that even in the absence of interventions, exposure to packaging under cold-chain conditions resulted in very low (under 2.0×10^{-3}) fomite-mediated risks.

We then evaluated the risk reductions from standard infection control interventions. Masking reduced risk by 20.6% (1.2×10^{-3} risk per 1h-period, 5th – 95th percentile: 1.5×10^{-6}, 9.4×10^{-3}), handwashing by 97.4% (3.9×10^{-5} risk per 1h-period, 5th – 95th percentile: 6.6×10^{-8}, 2.9×10^{-4}), and handwashing with masking by 99.4% (8.5×10^{-6} risk per 1h-period, 5th – 95th percentile: 2.8×10^{-8}, 6.6×10^{-5}), relative to no interventions. Similarly, Pitol and Julian (2021) demonstrated that hand hygiene could substantially reduce the risk of SARS-CoV-2 transmission from contaminated surfaces. In an 8-hour shift, cumulative fomite risks remained very low (handwashing and masking: 7.6×10^{-5} [5th – 95th percentile: 1.7×10^{-7}, 5.8×10^{-4}]). To contextualize these risks, handwashing and masking effectively reduce risk across varying exposure durations and to well below WHO risk guidelines for drinking water (*Cryptosporidium* [9.5×10^{-4}], *Campylobacter* [7.3×10^{-4}], and rotavirus [2.4×10^{-3}]) (WHO, 2017).

The addition of plastic surface decontamination to these standard infection control interventions reduced risks by 100% (1.2×10^{-8} risk per 1h-period, 5th – 95th percentile: 1.9×10^{-11}, 9.5×10^{-8}), relative to no interventions. Because risk reductions from masking and handwashing (99.4%, 8.5×10^{-6} risk per 1h-period) already fell well below risk targets of 1×10^{-4} (Ryan et al., 2014; Wilson et al., 2021), additional decontamination of frozen food packaging suggested minimal added benefit in risk reduction.

3.2. *Impact of vaccination on SARS-CoV-2 fomite-mediated infection risks to workers*

Vaccination of the susceptible worker with two doses of mRNA vaccine, without additional infection control interventions, reduced infection risk by 93.7% (optimal vaccine efficacy [VE] 86–99%: 9.6×10^{-5} risk per 1h-period, 5th – 95th percentile: 6.2×10^{-7}, 9.6×10^{-4}), relative to no vaccination (Fig. 2A). Optimal VE (86–99%) combined with infection control interventions further enhanced the risk reduction by 95.0% (masking: 7.5×10^{-5} risk per 1h-period, 5th – 95th percentile: 9.9×10^{-8}, 7.4×10^{-4}), 99.8% (hourly handwashing: 2.4×10^{-6} risk per 1h-period, 5th – 95th percentile: 4.4×10^{-9}, 2.3×10^{-5}), and 100% (hourly handwashing and masking: 5.2×10^{-7} risk per 1h-period, 5th – 95th percentile: 1.8×10^{-9}, 5.4×10^{-6}), relative to no vaccination

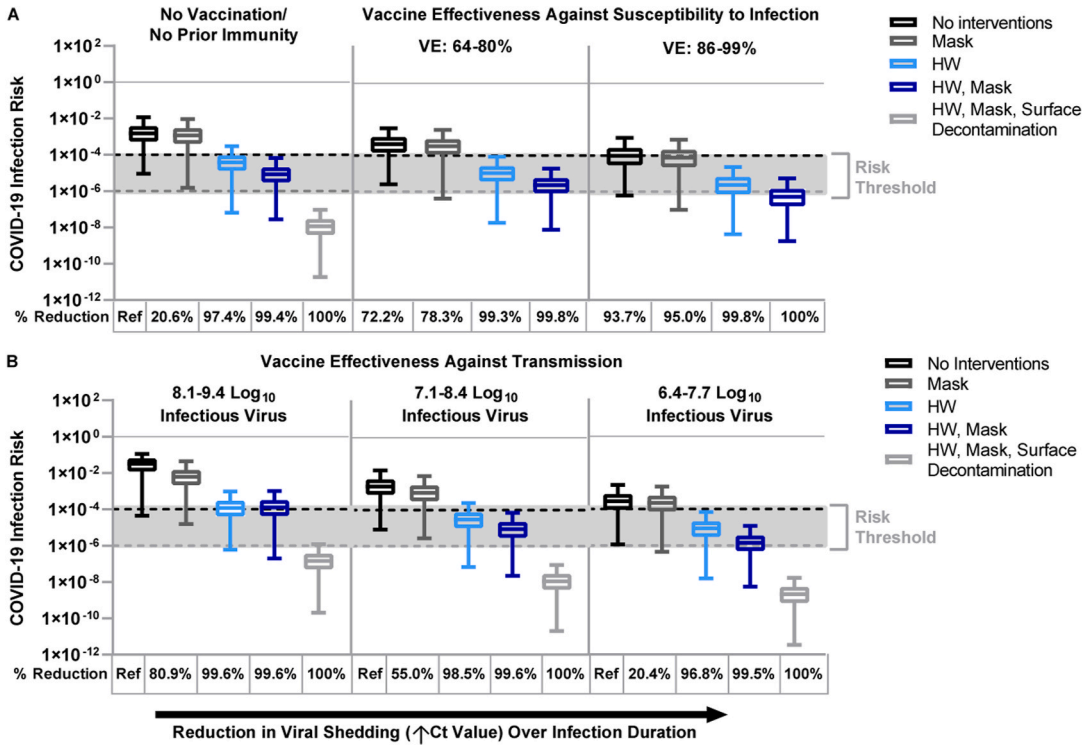

Fig. 2. Fomite-mediated SARS-CoV-2 infection risks associated with individual and combined standard infection control interventions (hourly handwashing of ungloved hands [2 $\log_{10}$ virus removal efficiency] (Grove et al., 2015), surgical masking). Vaccination was incorporated into the model representing two doses of mRNA vaccine (Moderna/Pfizer) and was applied with and without the standard infection control interventions. Additional decontamination of plastic packaging [3 $\log_{10}$ virus removal efficiency] (EPA, 2020) was applied in combination with the standard infection control interventions. Ventilation (two air changes per hour [ACH]) was applied to all simulations. An infectious to non-infectious particle ratio of 1:100 (Pitol & Julian, 2021) was applied to all viral shedding concentrations. Reductions in SARS-CoV-2 infection risk (%) to the susceptible worker relative to no interventions are reported below each panel. Panel A represents the impact of standard infection control interventions with and without vaccination on fomite-mediated SARS-CoV-2 risk. For the first vaccination scenario, we assumed only the susceptible worker was vaccinated with two doses of mRNA vaccine (Moderna/Pfizer) and vaccine effectiveness (VE) against susceptibility to infection was simulated across three vaccination states. These included: 1) no vaccination/no prior immunity; 2) lower VE ranging from 64% (Moustsen-Helms et al., 2021) - 80% (Khan & Mahmud, 2021) representative of reduced protection (variants of concern, waning immunity, immunocompromised and elderly or at-risk populations); and 3) optimal VE ranging from 86% (Andrejko et al., 2021; Pawlowski et al., 2021) – 99% (Swift et al., 2021) among healthy adults 14 days or more after second mRNA dose. Panel B: the second vaccine scenario represented vaccine effectiveness against transmission, where all workers are assumed to be vaccinated with two doses of mRNA vaccines and hence the model simulated breakthrough infections. Vaccine effectiveness against transmission (VET) was modeled by applying the combined effect of the reduction in risk of infection to the susceptible worker and the risk of transmissibility given a breakthrough infection among the vaccinated workers. We used the VET estimate (88.5% [95% CI: 82.3%, 94.8%]) derived from Prunas et al. (2021). VET was modeled across a range of three peak infectious viral shedding concentrations representative of possible increased transmissibility and/or infectiousness of variants of concern: 1) 8.1–9.4 $\log_{10}$ viral particles; 2) 7.1–8.4 $\log_{10}$ viral particles; and 3) 6.4–7.7 $\log_{10}$ viral particles. These viral shedding levels represent 100-, 10-, and 2-times, respectively, the increased viral shedding concentration simulated in the base model analysis. Dashed lines represent 1:10,000 (black) and 1:1,000,000 (gray) infection risk targets. Results are presented as the median risk values with 5th and 95th percentile bars.

(Fig. 2A). Across all vaccination states (no vaccination/no partial immunity, reduced VE 64–80%, and optimal VE 86–99%), combined handwashing and masking ensured SARS-CoV-2 fomite-mediated infection risks ranged between 8.5×10^{-6} (no vaccination) to 5.2×10^{-7} (optimal VE).

Importantly, these VE ranges encompass uncertainties in vaccine effectiveness with waning immunity (Wang et al., 2021) and emerging SARS-CoV-2 variants (Liu et al., 2021), heterogeneity in vaccine effectiveness, and variable vaccine protection among higher-risk populations (Monin et al., 2021). Based on these results, fomite-mediated risks will continue to decrease with increased vaccination rates among food workers.

3.3. Impact of infection control interventions on SARS-CoV-2 fomite-mediated risk to workers from new variants of concern (VOC)

To account for variations in the infectiousness of new VOC, we simulated increased viral shedding concentrations (2-, 10-, and 100-fold) resulting from breakthrough infections among a fully vaccinated workforce (two doses of Pfizer/Moderna; vaccine effectiveness against transmission (VET) 88.5% [5th – 95th percentile: 82.3%, 94.8%]) (Prunas et al., 2021). Ten-fold increased viral shedding (7.1–8.4 $\log_{10}$ infectious virus) resulted in an infection risk of 2.0×10^{-3} per 1h-period (5th – 95th percentile: 8.4×10^{-6}, 1.6×10^{-2}) (Fig. 2B). Handwashing and masking substantially reduced this risk by 99.6% (8.8×10^{-6} risk per 1h-period, 5th – 95th percentile: 2.3×10^{-8}, 7.0×10^{-5}), relative to no interventions. Similar trends were observed when using a 2-fold increased viral shedding. In the rare event of a VOC inducing a 100-fold increased viral shedding (8.1–9.4 $\log_{10}$ infectious virus), handwashing and masking still led to small fomite-mediated risks of 1.3×10^{-4} risk per 1h-period (5th – 95th percentile: 2.0×10^{-7}, 1.0×10^{-3}). Although new data on SARS-CoV-2 B.1.617.2 (Delta) and other VOCs continue to emerge (B.1.1.529 [Omicron]), the analysis presented here captures the increased viral shedding of Delta (median 7.83 log10 copies/mL [range: 6.3–8.83 log10 copies/mL]), which is estimated to be ten times higher and 40–60% more transmissible than historical variants (Callaway, 2021; Teyssou et al., 2021).

Risks from this study are conservative estimates of fomite-mediated transmission. Because the fraction of SARS-CoV-2 that enters mucous membranes via fomite-mediated transmission is likely smaller than

through intranasal administration (basis of dose-response model), our model may overestimate fomite-mediated risks. Moreover, viral decay during product transport to the receiving warehouse was not included in the primary risk analysis given sparse data on viral stability on surfaces at 4 °C and below (DHS, 2021b; Riddell et al., 2020). When incorporating viral persistence data from laboratory studies conducted at 5 °C on surfaces (Kwon et al., 2021), extended transport duration (30–90 days) reduced risk by 2.2–6.9 $\log_{10}$, relative to the baseline scenario (*Appendix A Supplementary data*). Further, while analyses in this study were conducted with a 1:100 infectious to non-infectious particle ratio (Pitol & Julian, 2021), fomite-mediated transmission will be even less likely with ratios of 1:1,000–1:1,000,000, as studies suggest (McCormick & Mermel, 2021).

4. Conclusion

Susceptible workers (unvaccinated, no precautions) in frozen food facilities are at low risk of SARS-CoV-2 fomite-mediated transmission under cold-chain conditions. Standard infection control interventions (masking and handwashing) reduced risk (8.5×10^{-6}) below the target of 1×10^{-4} (Ryan et al., 2014; Wilson et al., 2021). Thus, handwashing and masking mitigate the likelihood of transmitting SARS-CoV-2 via fomites into non-SARS-CoV-2 circulating areas (Ji et al., 2021; Liu et al., 2020). Across all vaccination states of the worker, handwashing with masking maintained low SARS-CoV-2 infection risks: 10^{-6} (no vaccination) to 10^{-7} (optimal VE). Therefore, worker vaccination should continue to be prioritized with standard infection control interventions (Hagen, 2021). Lastly, we found that the added benefit of decontaminating packaging (1.2×10^{-8} risk) was nominal and might be excessively conservative.

Surface decontamination of products meant for human consumption increases risks to workers and consumers. Continuous exposure to disinfectants was associated with respiratory diseases, including worsening asthma control (Dumas et al., 2017) and increased risk of chronic obstructive pulmonary disease (Dumas et al., 2019). Risks to consumers of ingested disinfectants through damaged packaging could range from irritation (sinuses, skin, eyes) to liver damage, depending on the disinfectant type and quantity (Kuehn, 2020; Li et al., 2020). Increasing disinfectant use since the start of the COVID-19 pandemic has resulted in a 16.4% increase in exposure calls as reported by the U.S National Poison Data System, CDC (January–March 2019) (Chang et al., 2020).

Furthermore, testing imported frozen foods for SARS-CoV-2 and disinfecting packaging (Liu et al., 2020) potentially introduces delays in product distribution, which could jeopardize product integrity, contribute to food spoilage, and lead to shortages or instability in the global food supply (Cable et al., 2021). Increased use of disinfectants are costly, with global sales of surface disinfectant in 2020 increasing by more than 30%, compared to 2019 (totaling US$4.5 billion) (Lewis, 2021). Thus, additional surface decontamination of cold-chain food packaging could be viewed as excessive and is more likely to increase chemical risks to workers, food hazard risks to consumers, and unnecessary added costs to the global food industry. These results support the continued use of global (WHO, 2020b; Cockburn, 2020) and U.S. federal (FDA, 2020) SARS CoV-2 risk mitigation strategies (handwashing, masking, vaccination) to advance the safety of essential food workers, maintain global food supply chains, and ensure consumer food security (Cable et al., 2021), even with future higher transmissible variants.

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Julia S. Sobolik: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Funding acquisition. **Elizabeth T. Sajewski:** Conceptualization, Methodology, Writing – review & editing. **Lee-Ann Jaykus:** Conceptualization, Methodology, Visualization, Writing – review & editing. **D. Kane Cooper:** Methodology, Validation, Writing – review & editing. **Ben A. Lopman:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Alicia N. M. Kraay:** Conceptualization, Methodology, Writing – review & editing. **P. Barry Ryan:** Conceptualization, Methodology, Writing – review & editing. **Jodie L. Guest:** Conceptualization, Methodology, Writing – review & editing. **Amy Webb-Girard:** Conceptualization, Methodology, Writing – review & editing. **Juan S. Leon:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare no competing interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodcont.2022.108845.

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