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**Identification of Mitigation Measures to Prevent Norovirus Outbreaks in Indoor Food Production Facilities via Quantitative Microbial Risk Assessment Modeling**

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Bachelor of Science
McGill University
2019

Thesis Committee Chair: Juan S. Leon, PhD, MPH

An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
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2022

## Abstract

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By Isabelle Flinn

Norovirus is the leading cause of acute gastroenteritis in the United Sates with outbreaks of norovirus often linked to contaminated food. Infected food production workers may contaminate their work environment posing a risk of infection to their fellow workers. The purpose of this study was to quantify the cumulative risk of norovirus infection for a susceptible food production worker exposed to specific exposure events (fecal and vomit) and transmission pathways (fomite and aerosol). Additionally, the impact of mitigation measures (hand hygiene, surface disinfection, and masking) on the risk of norovirus infection for a susceptible food production worker were evaluated. A Quantitative Microbial Risk Assessment Model was created in R using the mc2d package for two-dimensional Monte Carlo simulation and was iterated over 10,000 simulations. Fomite and aerosol-mediated norovirus transmission pathways were examined for an infected worker experiencing either repeated fecal (fomite) or a single vomit (aerosol, fomite) event. In the absence of mitigation measures, the risk of norovirus infection associated with an 8-hour cumulative exposure varied by exposure event: fecal scenario (22%), and vomit scenario (0.53%). Compared to no mitigation measures, combined intervention utilization (hand washing, glove use, surface disinfection, and masking) resulted in a maximum reduction in the risk of infection of 99% in the fecal scenario and 96% in the vomit scenario. These findings provide insight into variation in the risk of norovirus infection by exposure event and transmission pathway, with exposure to norovirus contamination from fecal events posing the greatest risk. The findings of our model can be leveraged by the food production industry to minimize the infection risk associated with specific norovirus exposure events and transmission pathways through the prioritization of mitigation measures.

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# 1. Literature Review

## 1.1 Norovirus Burden of Disease in the United States

Norovirus is the leading cause acute gastroenteritis (AGE) in the United States [1, 2]. Norovirus was first identified in 1972 [3] and has continued to cause disease with increasing frequency of outbreaks in the US with 364 reported outbreaks in 2008 to 2,429 reported outbreaks in 2018 [4]. Norovirus is known to display seasonal variability with 71-82% of outbreaks occurring in the winter months [5-7]. In the US, an estimated 19-21 million cases of vomiting and diarrhea are attributed to norovirus infections each year [2, 8]. This corresponds to over 2 million outpatient clinic visits, 465,000 emergency department visits, more than 100 thousand hospitalizations and 900 deaths each year [8]. The lack of long-term and cross immunity contributes to norovirus' ability to cause repeat infection and illness [9, 10]. It has been estimated that everyone in the US will experience five norovirus related illnesses in their lifetime [2].

While norovirus is the leading cause of AGE in the US, the actual disease burden of norovirus is likely underestimated [8]. There are two reasons for that under estimation of cases. One, symptoms usually begin 12-48hr after exposure and last from 1-3 days [11, 12]. Due to the short duration of symptoms, many infections go untested and un-identified by local health departments [2]. Compounding the issue of under estimation of cases is the fact that there are currently no individual case reporting requirements [2, 13]. In an effort to increase reporting and access to norovirus outbreak data, the Centers of Disease Control and Prevention (CDC) developed the National Outbreak Reporting System (NORS) in 2009 [14]. In the same year, the CDC established a norovirus outbreak laboratory surveillance network, CaliciNet. This laboratory network includes federal, state, and local public health laboratories in the US [13, 14].

Both of these systems provide valuable data on and surveillance of norovirus outbreaks across the US.

### 1.2 Norovirus Outbreaks

Outbreaks of norovirus are common with approximately 2,500 reported outbreaks in the US each year [8]. Outbreaks of norovirus occur in a variety of settings including, healthcare facilities, restaurants and food cratering settings, schools from childcare to university settings, and on cruise ships[15-17]. In the US, norovirus outbreaks are often linked to contaminated food with approximately 16% of outbreaks being traced back to a food source [18]. From 1998 to 2013, contamination of fresh produce resulted in over 400 reported outbreaks [19]. Other foods including delicatessen meats, wedding cakes, and a variety ready to eat foods such as sandwiches and salads have all been implicated in outbreaks of norovirus [20-22]. Food handlers are often the source of food contamination in these outbreaks [19-21, 23, 24]. In the case of the delicatessen meat outbreak, 137 persons became ill [20]. The meat in question had been sliced by a food production facility worker one day after recovering from gastroenteritis. After preparation by the infected worker, the meat was vacuum-packed, frozen, and subsequently consumed by cases. Norovirus sequences were identified in the stool samples obtained from several cases and from the meat packaging [20]. In another investigation of a norovirus outbreak, 332 cases were traced back to 46 weddings occurring over the same weekend. All the weddings in question had wedding cakes from the same bakery. It was discovered that two bakery employees had experience a norovirus likely illness during the week leading up to the wedding. Identical norovirus sequences were identified from cases and an ill bakery employee [21].

Norovirus outbreaks may be due to contamination at specific steps along the farm to fork chain [25, 26]. The farm to fork chain encompasses the pathway and production steps that food produced on farms follows from the farm to the consumer's "fork". This pathway can be conceptualized in four stages: farm production, processing, distribution, and consumer, with contamination most likely to occur during the first, second, and final stage [27]. The first stage takes place on the farm and contamination can occur during pre- or post-harvest process. Pre-harvest norovirus contamination can occur from use of contaminated irrigation water [28]. Post-harvest contamination can occur from contact with the contaminated hands of a harvester [29]. In a review by Bozkurt et al., the main source of preharvest and postharvest contamination was due to infected food handlers [30]. The second stage takes place at food production facilities where the food undergoes processing and packaging. Contamination can occur from contact with the contaminated hands of a production worker [31]. One study identified norovirus on 31% of field and packinghouse worker hands and on 30% of green bell papers handled and packaged by these workers [31]. A systematic review by Van Pelt et al. found the median prevalence of norovirus on farm produce (e.g. raspberries, tomatoes, lettuce) to be 30% across multiple countries including US, Mexico, Poland and Spain to name a few [32]. The third stage is the distribution of food to the point of sale or transport to storage prior to distribution. Currently there are no reports of norovirus contamination during transport to storage or distribution available. The final consumer stage takes place at the consumers place of food preparation and consumption. Contamination at this stage can occur from contact with the contaminated hands of the consumer or contaminated preparation surfaces [28].

Despite the documented presence of norovirus in the food production facility setting and the documented presence of infected workers there is no available information on norovirus outbreaks among food production workers. Given the low infectious dose [33] and various modes of transmission of norovirus [34] it is likely that transmission and outbreaks are occurring in the food production facility setting. Why there are no reported outbreaks in food production facility setting is unclear. It is possible that hesitancy to report illness exists among food production workers. Carpenter et al. found that restaurant workers often reported not wanting to burden the restaurant by leaving their co-workers short staffed as well as fear of losing their job if they could not work as reasons for working while sick [35]. Similar sentiments may be at play in the food production facility setting and may act as deterrents to reporting illness. It is also possible that cases are not reported because they are going undetected due to the short duration of symptoms [11].

### 1.3 Implications of Norovirus Outbreaks Among Food Workers

Sporadic norovirus cases and norovirus outbreaks have a significant economic impact. In the US, Bartsch et al. estimate that sporadic norovirus cases and outbreaks incurs 10.6 billion dollars in cost to each year [36]. Productivity loss is the largest driver of cost accounting for 89% of total costs. It has been estimated that foodborne outbreaks are responsible for 2.3 billion dollars in cost to society annually [37]. Mitigation measure to reduce food contamination along the farm to fork chain have been prioritized [38-42]. There are currently no estimates of industry specific cost and, as such, the impact of norovirus outbreaks among the food industry, such as in the food production setting, is unknown. The continuing COVID-19 pandemic has, however, made it clear that significant viral outbreaks, like norovirus, in the food production setting can have large scale economic, supply chain, and workforce impacts [43, 44].

For infected food workers, norovirus not only impacts their health but also their livelihood as they are unable to work due to furlough regulations in place to protect public health. The Food and Drug Administration (FDA) Food Safety Modernization Act requires that individuals be excluded from working in settings where their presence may result in contamination of produce or food contact surfaces [45]. This regulation applies to ill food production workers and often results in worker exclusion from work for a minimum of 48 hours after symptoms have resolved [46-48]. Studies have shown that worker furlough can avert a significant number of norovirus infections. One study determined that 75% of norovirus infections could be averted in a retail food setting with worker furloughs until 24 hours after symptom resolution relative to the baseline model [49]. Yang et al. estimated that 12.7 million US norovirus cases could be averted annually with 100% compliance with food worker furlough until 48 hours after symptom resolution [48]. While important to promote worker health and food safety, these furloughs may also act to deter reporting of illness due to the loss of work hours and thereby loss of income for workers when companies are not able to provide paid sick leave.

The potential financial and health impacts of norovirus infection for food production workers, as well as the potential for infected workers to infect susceptible co-workers and contaminate food products with norovirus necessitate the quantification of the risk of transmission of norovirus and identification risk mitigation measures in these setting. Mitigation measure will serve to protect worker health as well as increase food safety. Protecting workers from being infected with norovirus reduces the risk of norovirus contamination of food at the production level and decreases the potential for norovirus outbreaks among consumers and the broader community. This reduction in norovirus outbreaks and community transmission is important for maintaining broader community health and preventing economic burden due to illness from norovirus.

### 1.4 Transmission Routes of Norovirus

Norovirus is highly infectious and is transmitted via the fecal oral route as well as through infectious vomitus [28]. An individual is exposed to norovirus by ingesting norovirus contaminated fecal or vomitus particles of a norovirus infected individual. With an infectious dose of as few as 18 viral particles needed to cause infection, contamination of food, water, and surfaces may not be readily apparent [33]. Furthermore, this dose is easily achieved for a susceptible individual as infected individuals have been found to shed billions viral particles per gram of stool [50]. Shedding of viral particles can begin before symptom onset or in the absence of symptoms, as is the cases in asymptomatic infections, and in some cases can last up to 8 weeks after infection [50]. Norovirus is also a very hardy virus able to withstand freezing to 140-degrees Fahrenheit (60ºC) temperatures [51, 52]. This ability to withstand such a wide temperature range contributes to norovirus ability to persist on surfaces and survive kills steps during food production and preparation [30]. There are many modes through which exposure to norovirus can occur including consumption of contaminated food, water, contact with contaminated fomites, as well as person-to-person transmission [34].

#### 1.4.1 Foodborne Transmission

There are many modes through which exposure to norovirus can occur including consumption of contaminated food. Feces and vomitus of infected individuals are the source are norovirus contamination of food. Infected food handlers are often the main source of contamination of food products. According to the CDC, 70% of reported food related outbreaks are caused by an infected food worker [23, 24]. There are several possible modes for the contamination of food including contact with an infected individual, such as the contaminated hands of infected food worker, contact with contaminated surfaces, such as contaminated food processing or preparation surfaces, and use of contaminated water, such as contaminated irrigation water or ground water [20, 31, 53, 54]. Contaminated food, if consumed, can go on to cause infection in the individual. In two different studies, Verhoef et al. found that approximately 1 in 7 norovirus outbreaks are attributed to food and an estimated 7% of foodborne norovirus outbreaks are part of an international outbreak [18, 55].

Contamination of food, especially ready to eat produce, in the food production setting is an important concern. Many produce products are ready-to-eat and if contaminated with norovirus can cause infection in consumers. Food handlers, contaminated water, and fruit pickers have been implicated as the source of contamination that lead to several outbreaks [30]. The washing, freezing, and frozen storage process that produce, such as frozen berries, go through during food production are not able to inactivate or remove norovirus [30]. It has been reported that 54% of produce associated outbreaks are caused by norovirus [19]. From 1983-2018, norovirus was the most common cause of reported berry related outbreaks, implicated in 46 outbreaks with over 15,800 cases globally [30]. This highlights the importance of reducing the opportunity for contamination events in the food processing and production setting as these goods if contaminated can seed local and even international outbreaks [20, 21, 30, 55].

### 1.4.2 Waterborne Transmission

There are many modes through which exposure to norovirus can occur including consumption of contaminated water. Transmission of norovirus via water can occur when contaminated water is ingested or used in the produce growing or production process which is later consumed. Water may become contaminated with infectious norovirus fecal matter when human sewage is able to mix with the water source [56]. This can occur when there is a leak in a septic tank, when water is not properly treated, or if an infected person vomits or defecates in the water [28]. Recreational, drinking, and farm irrigation water can be contaminated with norovirus [28, 57]. If the contaminated water is ingested either directly through drinking or indirectly by consuming ready to eat foods grown or prepared with contaminated water, norovirus infection in the host can occur [58]. It has been shown that norovirus can remain infectious for at least 61 days and can be detected for over three years in ground water [59].

### 1.4.3 Fomite Mediated Transmission

There are many modes through which exposure to norovirus can occur including contact with contaminated fomites. Fomite mediated transmission of norovirus may occur when a person or food comes in contract with a contaminated surface or object and that contamination is ingested by the individual. Contamination of fomites occurs when either fecal matter or vomitus of an infected individual lands on or is transferred to the fomite. The role of fomites in norovirus transmission has been documented in several outbreaks including those in hotels, long term care facilities, cruise ships, and schools [54, 60-64]. A report of multiple outbreaks occurring on the same cruise ship over several sequential cruises indicated that contamination of ship surfaces was likely perpetuating the outbreaks [64]. Contaminated computer equipment was identified as contributing to norovirus transmission during an outbreak at an elementary school [63]. Due to its high stability, norovirus can persist even after an outbreak has ended and cause new infections in individuals who come in contact with a contaminated surface [65]. In the food production setting, contaminated fomites can contaminate food products as well as lead to infection in food workers.

### 1.4.4 Person-to-Person Transmission

There are many modes through which exposure to norovirus can occur including person-to-person transmission. Person-to-person transmission is recognized as the most common mode of transmission of norovirus [28]. Person-to-person transmission of norovirus occurs when a susceptible individual is directly exposed to the fecal matter or vomitus of an infected individual. This can occur through direct contact with contamination on the infected individual resulting in contamination of the susceptible individuals' hands and subsequent ingestion of viral particles by the susceptible individual. Alternatively, the susceptible individual can be exposed to infectious bodily fluids during expulsion from the infected individual leading to subsequent ingestion of infectious fluids. Person-to-person transmission contrasts with the other routes of transmission in that it does not involve an intermediary reservoir between the infected and susceptible individuals like food, water, and fomite mediated transmission.

One mode of person-to-person transmission via exposure to infectious fecal matter occurs when a susceptible individual is exposed to and ingests infected fecal matter. When proper hand hygiene is not practiced by an infected individual, norovirus particles can remain on the individuals' hands [28]. This contamination can be transmitted to a susceptible individual through direct hand to hand contact or contact between the contaminated hand and another body part of the susceptible person. This contamination may then be ingested by the susceptible person transferring the contamination into their mouth.

Another mode of person-to-person transmission via exposure to infectious vomitus occurs when vomit droplets or aerosols are ingested by a susceptible individual [28]. Exposure to vomitus may occur unexpectedly as some infected individuals go from feeling fine to projectile vomiting in a matter of minutes [66]. The latter event can lead to the exposure of individuals, who are nearby, via exposure to vomitus droplets or aerosols. Several studies in hospitals have identified norovirus RNA in the air inside as well as outside infected patient rooms at various intervals after the patient experienced a vomiting event [67, 68]. Another study supporting the possibility of airborne spread of norovirus found that housekeepers who walked through or visited the emergency department during an outbreak had a 4 times greater risk of becoming ill [69]. Potential exposure to aerosol mediated transmission is not limited to hospitals. During an outbreak investigation at a hotel restaurant, it was determined that a vomiting event by a diner resulted in aerosol mediated transmission of norovirus as diners further away for the ill diner were less likely to be cases in the outbreak [66].

### 1.4.5 Exposure Routes Relevant to Food Production Activities on the Produce Production Floor

While there are many modes of transmission of norovirus, via contaminated food, water, fomites, or person-to-person, this analysis will only explore transmission via contact with contaminated fomites and person-to-person transmission on a produce production floor. A produce production floor is the space in produce processing facilities where raw agricultural materials undergoes processing, transformation into final product, and packaging [70].

Specifically, we are interested in fomite mediated transmission that occurs when a susceptible worker touches packaging contaminated by an upstream infected worker along the production line. We will also consider fomite mediated transmission via contact with a contaminated door handle of a door to the production area. The other scenario we will consider will be a vomiting event in which the susceptible worker will be exposed to aerosolized vomit and fomite mediated transmission from vomit contamination of the conveyer belt. For both these scenarios we will identify mitigation measure to reduce the risk of transmission to the susceptible worker.

### 1.5 Mitigation Measures to Protect Workers from Norovirus Infection

Federal guidelines and legislation provide guidance and requirements for mitigation measure to protect both worker health and food safety. The Occupational Safety Health Administration (OSHA) provide guidelines for industry aimed at protecting worker health. OSHA requires that workers have ready access to handwashing facilities, personal protective equipment, and EPA-registered surface disinfectants [39, 40, 42]. The requirements laid out by OSHA serve a dual function of protecting both worker health and enhancing food safety. Other regulatory agencies, such as the FDA, provide guidance and legislation that is aimed at enhancing food safety, however these guidelines often indirectly function to protect worker health. The FDA food safety modernization act (FSMA), enacted in 2011, as well as the Produce Safety Rule and Preventive Controls for Human Food (PCHF), both part of the FSMA enacted in 2015, set forth rules and standards aimed at minimizing contamination of fresh and processed produce [38, 71]. These federal regulations reduce foodborne disease risks thereby enhancing the safety of the US food supply [71]. The FSMA outlines requirement for workers handling produce including hygiene, training, and exclusion of ill workers [41, 45]. These requirements not only act to enhance food safety but also to promote worker health.

In accordance with these federal regulations, food production companies employ measures to both protect worker health and mitigate the contamination of produce during production. Mitigation measures that have been identified by studies as impactful for the prevention of norovirus contamination in the retail and food production setting include proper hand hygiene, gloving, and worker furlough [72, 73]. Each of these measures helps disrupt different norovirus transmission pathways. Hand hygiene and gloving disrupt the potential for contamination of foods, fomites, and person-to-person transmission. By preventing contamination, these mitigation measures prevent exposure of susceptible individuals to contaminated foods, fomites, and other individuals. Exclusion of ill workers prevents food, fomite-mediated, and person-to-person transmission by excluding the infected individual from the food production environment.

### 1.6 Quantitative Microbial Risk Assessment Frameworks Applied to Worker Health

QMRA modeling allows for the characterization of the risk of infection, for the modeled scenarios, using a dose-response model [74]. QMRA models have been applied to many different pathogens and scenarios [73, 75-77]. Surprisingly, few QMRAs have been applied to worker health. One QMRA model quantified the risk associated with inhalation of bioaerosols contaminated with human adenovirus across different occupational settings to identify which setting posed the highest risk of infection [78]. The QMRA model found that of the occupational settings evaluated, including wastewater systems, solid waste landfills, and toilets in healthcare settings and offices, toilets posed the greatest probability of infection at nearly 100% probability based on exposure time and setting [78]. Over the course of the COVID-19 pandemic, much more attention has been paid to worker health particularly in the food production setting. Two different QMRA models evaluated the risk of SARS-CoV-2 infection, via different transmission pathways, for food production workers and found that evaluated mitigation measures (physical distancing, hand hygiene, surface disinfection, mask use, air exchange rate) were able to reduce the risk of infection to workers below 1% for combined intervention use [79, 80]. No norovirus QMRA models have been applied to food production worker health.

QMRA modeling is comprised of four steps, hazard identification, exposure assessment, dose-response, and risk characterization [81]. The first step, hazard identification, involves identifying the relevant parameters of pathogen and the human illness of concern [81, 82]. This is followed by exposure assessment which involves determining the dose that someone will be exposed to. This dose is determined through thousands of successive simulations of the probabilistic model that represents the exposure, in this case transmission, pathways of interest [81, 82]. Next a dose response model is selected. The risk is characterized by feeding the calculated dose into the dose response model which will output the risk a person has of becoming infected from the modeled scenarios.

QMRA models not only allow for the quantification of infection risk but the identification of effective risk reduction measures such as proper hand hygiene, personal protective equipment (PPE) use, surface disinfection [73]. By incorporating risk reduction measures in the QMRA model structure, the output risk will represent the risk of infection for an individual who utilizes these risk reduction measures. This allows for the theoretical evaluation of mitigation measures and quantification of the most impactful combination of measures. While the QMRA modeling frameworks allows for a great deal of flexibility in modeled scenarios, models are limited by unreliable model parameters [83]. Parameter variability, the heterogeneity in a parameter value, and uncertainty, lack of knowledge of the true value, can be addressed through sensitivity analysis which quantifies the propagation of variability and uncertainty. This allows for the identification of influential parameters on the infection risk output by the model [83-85].

The QMRA framework has been used to quantify the risk of norovirus infections along the farm-to-fork chain [29, 73, 76, 77]. The QMRA framework is able to quantify the cumulative risk from multiple exposure pathways along the farm to fork chain. The QMRA framework is also able to evaluate mitigation measures at various steps along the farm to fork chain. Studies quantifying infection risk along the farm-to-fork chain usually focus on the risk of infection to consumers due to contamination of food from environmental sources during food production or from infected food workers [29, 49, 73, 76, 77]. Mitigation measures are often evaluated in these contexts for their ability to reduce food contamination and thus the ability to reduce the risk of infection to consumers. At the time of writing, no studies have quantified the risk of norovirus infection to produce production workers working on the production floor with an infected worker or the impact of mitigation measures on this risk.

### 1.7 Need, Objectives, and Significance of the Present Study

Thus, the need of this study is to prevent norovirus outbreaks among produce workers in produce production facilities. To address this need, the objectives of this study are to 1) identify the cumulative risk associated with specific norovirus transmission pathways on the food production floor, 2) quantify the impact of combined mitigation strategies on the risk of norovirus infection among food production floor workers.

This work will highlight the importance of protecting worker health in maintaining the safety of the US food supply. By fulfilling objective 1 and quantifying the cumulative risk, industry and regulatory agencies will be able to better inform their guidance and policies around worker health. Depending on the magnitude of risk, new policies may be needed to enhance worker health and safety. By fulfilling objective 2 and identifying the impact of mitigation strategies, this research will help industry and regulatory agencies understand the effectiveness of existing mitigation measure and requirements. Fulfilling both objective 1 and 2 will aid the food production industry in preventing norovirus outbreaks among food production workers. This could be particularly important over the next year as norovirus cases have been lower over the course of the COVID-19 pandemic, compared to prior to the pandemic, and any immunity that may have existed may be reduced thus creating an environment with heightened outbreak potential [86, 87].

# 2. Methods

## 2.1 Model Overview & Structure

Model conceptualization was informed by norovirus QMRA and quantitative exposure models, SARS-CoV-2 QMRA models, as well as vomiting simulation studies [72, 73, 79, 80, 88, 89]. The norovirus QMRA models provided insight into the mechanism of fomite mediated transmission particularly as it relates to fecal contamination on worker hands. The SARS-CoV-2 QMRA models were leveraged to structure the aerosol mediated transmission pathway in the vomit event scenario. The vomiting simulation studies provided the basis for defining the projectile vomit trajectory and contamination of the production room environment.

The outcomes of the model included the risk of norovirus infection for a susceptible worker exposed to different exposure events (fecal, vomitus) and transmission pathways (fomite, aerosol). The susceptible worker's risk of infection was defined as the risk from ingesting infectious norovirus particles (infectious feces or vomitus) via transfer from the hand to mouth or ingestion of infectious aerosols (vomit). Additional outcomes included the cumulative infection risk reduction achieved through the utilization of mitigation measures (hand hygiene, surface disinfection, and face mask use). Figure 1 illustrates the exposure events and transmission pathways that were analyzed in the QMRA model.

The simulated transmission pathways begin with a single infected worker packaging products into boxes. The boxes progress down the production line to the downstream susceptible worker who palletizes the boxes. In the fecal event scenario, the infected worker contaminates their hands with feces leading to contamination of fomite reservoirs. The fecal module simulates an 8-hour work shift split into four 2-hour timesteps. In the fecal module, it is assumed that the infected worker uses the restroom to defecate, contaminating their hands in the process. The infected worker is modeled to contact available surfaces in the restroom leading to contamination of the restroom environment. Returning to the production floor, the infected worker's contaminated hands contact the production floor door handle contaminating it. The infected worker then returns to their workstation packing product into boxes leading to contamination of the boxes. The contaminated restroom environment, production room door handle, and product boxes subsequently acts as fomite reservoir for transmission when contacted by the hands of the susceptible worker.

The vomit module simulates an 8-hour work shift split into eight 1-hour timesteps. In the vomit module it is assumed that the infected worker experiences a sudden onset of projectile vomiting contaminating the floor, conveyer belt, nearby products on the conveyer belt, and the production room air. It is assumed that the infected worker is standing in front of and facing the conveyer belt when they experienced a sudden onset of nausea. The infected worker then turns their head and body to face towards the start of the production line (i.e., upstream), with the conveyer belt on one side of them, and immediately "projectile" vomits. The infected worker is removed from the production line, vomitus removed and disinfected, and the contaminated products disposed of. The disinfection of the conveyer belt removes only a proportion of the contamination resulting in the belt acting as a fomite reservoir. For the baseline modeled scenario, surface disinfection is assumed to be done hastily with a cloth soaked in detergent and used to produce a visible clean surface. Baker et al. found that use of a cloth soaked in detergent and used to produce a visible clean surface was insufficient to eliminate norovirus contamination [90]. In order to model a worst-case-scenario situation, it was assumed that disinfection with a cloth soaked in detergent would produce a 10% reduction in norovirus contamination (baseline). For the modeled surface disinfection intervention scenario, increased attention to cleaning and increased efficacy of cleaning products was modeled. A 90% (1 $log_{10}$) reduction in norovirus contamination (enhanced efficacy of surface disinfection) was modeled in accordance with previously quantified and modelled surface disinfection efficacies for the intervention scenario [72, 91]. Infectious aerosols produced during the vomiting event are available to be ingested during breaths taken by the susceptible worker during the remainder of the 8-hour work shift. Infectious aerosols are also available to fallout of the air contaminating the product boxes which act as fomite reservoirs throughout the remainder of the shift.

The model was developed in R (version 4.1.1; R Development Core Team; Vienna, Austria) using the mc2d package for Monte Carlo simulation and sensitivity analysis (Pouillot and Delignette-Muller, 2010) [92].

**2.2 Data Sources**

Model parameters (Table 1) are grouped into three categories (i) norovirus viral load and surface, room air, and worker hands contamination with infectious fecal matter or vomitus; (ii) worker health and hygiene behavior (handwashing efficacy, glove use, surface disinfection, mask use); and (iii) dose-response and risk characterization for the susceptible worker. Viral shedding data were obtained from human norovirus challenge studies in which symptomatic individuals shed 2 to 11 $log_{10}$ viral RNA genome copies per gram of feces and 3 to 7 $log_{10}$ viral RNA genome copies per mL of vomitus [72, 93-95]. The vomitus projectile trajectory, proportion of vomitus aerosolized, and particle size were obtained from vomiting simulation studies, epidemiologic reports of projectile vomiting events, and hospital air sampling studies [66, 68, 88, 96]. Parameters for the persistence and transfer of noroviruses from hands to gloves, hands to mouth, hands to fomites and from fomites to hands were obtained from laboratory-based studies

[72, 97-102]. The efficacy of hand hygiene, surface disinfection, and mask use were based on laboratory studies [72, 90, 103-115].

## 2.3 Transmission from a Fecal Event

In the fecal event simulation, the infected worker defecates and contaminates their hands. The infected worker's hands contact and contaminate the restroom environment. Before leaving the restroom, the infected worker is assumed to follow good manufacturing practices and washes their hands. After exiting the restroom, the infected worker's contaminated hands contact the production floor door handle and subsequently the product boxes leading to contamination of these surfaces. Once contaminated, the restroom environment, production floor door handle, and product boxes act as fomite reservoirs, facilitating fomite mediated transmission, when contacted by the hands of the susceptible worker. Interventions including additional handwashing during each 2-hour timestep, glove use, surface cleaning, and mask use are built into the following equations as "switches". These intervention "switches" can be turned "on" or "off" in the model code to model the use of interventions and determine the precent reduction in the risk of infection.

### 2.3.1 Contamination of Infected Worker Hands and Fomite Reservoirs

All fecal events were modeled to occurred in the restroom. During the restroom visit, the infected worker's hands are assumed to become contaminated via contact with personal feces. The infected worker is assumed to follow good manufacturing practices and washes their hands before leaving the restroom. Four restroom visits were simulated for the infected worker, one every 2 hours based on prior modelling assumptions and epidemiologic studies [49, 72, 116].

The initial contamination on one hand of the infected worker, after use of the restroom, $nvhandinf$, is expressed as norovirus virions per one hand:

$$nvhandinf = \frac{mfh \times nvf}{10^{HWeff}}$$

In the above equation, $mfh$, is the mass of feces per hand, $nvf$, is the concentration of norovirus in feces, and $HWeff$ is the removal efficacy of handwashing. While in the restroom, the infected worker contacts the restroom environment contaminating it and leading it to act as a reservoir for transmission. The concentration of norovirus that is transferred to the restroom environment, $BR.nv$ , is determined as follows:

$$BR.nv = concen.nv \times Trhbr \times contacts \times \frac{hand.sa}{counter.sa} \times (1 - sc.eff.p \times clean)$$

Where $concen.nv$ is the concentration of norovirus on both of the infected worker's hands, $Trhbr$ is the proportion of norovirus transferred per touch from the infected worker's hands to the restroom environment, $contacts$ is the number of hand to surface contacts, $hand.sa$ is the surface area of both hands, $counter.sa$ is the surface area of the restroom counter, $sc.eff.p$ is the efficiency of surface disinfection, and clean is the probability that the surface was cleaned.

Once the infected worker leaves the restroom to return to the production floor, they contact the production room door handle with one of their contaminated hands, $noro.left$, leading to contamination of the door handle. The amount of contamination that is transferred from the infected workers hand to the production floor door handle, $amtdoor$, is calculated using the proportion of norovirus transferred per touch from a contaminated hand to the door handle, $Trhdoor$, where s$a.handle$ is the surface area of the production floor door handle:

$$amtdoor = noro.left - \big(noro.left \times (1 - Trhdoor)\big) \times \left(\frac{hand.sa/2}{sa.handle}\right)$$

After contacting the production floor door handle the amount of norovirus contamination that remains on both hands of the infected worker, $nvHd$, is calculated as follows:

$$nvHd = \left(noro.left \times (1 - Trhdoor)\right) + noro.left$$

Upon returning to the production floor, the infected worker either puts on gloves if this intervention is being modeled, (i.e., if the intervention "switch" for Glove use is turned "on", or they do not don gloves, if the intervention "switch" is turned "off"). The intervention "switch" for glove use is modeled as the probability of a worker using gloves, $prob.glove$. A probability of 1 means that the worker put on gloves otherwise if the probability is 0 they did not. When the infected worker is simulated to don gloves, norovirus is transferred from the infected worker's contaminated hands, $nvHd$, to the gloves, $nvG$. The amount of norovirus transferred during the gloving process is calculated using the proportion of norovirus transferred per touch from a contaminated hand to the gloves, $Trhg$.

$$nvG = nvHd - nvHd \times (1 - Trhg) \times prob.glove$$

Upon return to their workstation, the infected worker contaminates the product boxes through contact with their contaminated hands. The amount of norovirus contamination on product boxes, $nvP1$, varies by glove use as follows:

$$if\ prob.glove1 > 0, nvP1 = nvG \times carton.number \times Trhp$$

$$else, nvP1 = nvHd \times carton.number \times Trhp$$

Where, $carton.number$ is the number of product boxes processed during the timestep, and $Trhp$ is the proportion of norovirus transferred per touch from a contaminated hand to the product box. The concentration of norovirus contamination on all product boxes processed during the timestep is represented by a composite fomite:

$$composite.fomite = \left({}^{nvP1}/_{contamcompcartSA}\right) \times \left({}^{hand.sa}/_{compcartonSA}\right)$$

Where, $contamcompcartSA$ is the composite contaminated product box surface area that the susceptible worker will come in contact with, $hand.sa$ is the surface area of the susceptible worker's hand, and $compcartonSA$ is the composite surface area of the product boxes processed during the timestep.

### 2.3.2 Fomite Transmission Modeling

Once contaminated, fomite reservoirs (the restroom environment, production floor door handle, and product boxes) pose subsequent infection risk to the susceptible worker. When the susceptible work's hands contact a fomite reservoir norovirus is transferred to their hands. During the 8-hour shift the susceptible worker uses the restroom once every four hours, once during timestep 2 and once during timestep 4. During the visits to the restroom the susceptible worker is exposed to the contaminated restroom environment and production floor door handle.

#### 2.3.2.1 The Restroom Environment & Production Floor Door Handle

When the susceptible worker leaves the production floor to use the restroom, they first come into contact with the contaminated restroom environment and then the production floor door handle when they return to the production floor. It is assumed that the restroom door is a swing door. This is an important assumption as it means that norovirus contamination is not transferred to a bathroom door handle by the infected worker leaving the bathroom and thus norovirus contamination is not subsequently contacted by the susceptible worker leaving the bathroom. It is also assumed that the susceptible worker follows good manufacturing practices and washes their hands before leaving the restroom. The amount of norovirus that the susceptible accumulates on their hands when visiting the restroom environment and contacting the production floor door handle is determined by:

$$SWh = \left(BR.nv \times Trbr \times hand.sa \times (1 - HWeff)\right) + (nvdoor \times Trdoorh)$$

In the above equation $Trbr$ is the proportion of norovirus transferred per touch of the restroom environment to the susceptible worker's hands, $nvdoor$ is the concentration of norovirus on the production floor door handle, and $Trdoor$h is the proportion of norovirus transferred per touch of the door handle to the susceptible workers hands. If the susceptible worker does not use the restroom within a 2-hour timestep they do not accumulate contamination on their hands from the bathroom environment or production floor door handle.

### 2.3.2.2 Product Boxes

During each timestep the susceptible worker also comes into contact with the contaminated product boxes while palletizing the boxes for distribution. The amount of norovirus contamination that is transferred to the workers hands from contact with the product boxes during the given timestep, $Chand.1$ for the first timestep, variers by whether the worker changes their gloves during the timestep:

$$if\ prob.gloves > 0,$$

$$Chand.1 = \left(\left(\frac{freq.hs \times composite.fomite \times Trph}{v.decay.min.hand}\right) \times \left(1 - e^{(-v.decay.min.hand\ \times time)}\right)\right) \times (1 - HWeff * prob.hw)^{Freq.HW} \times (1 - Trhg)^{\ Freq.glove}$$

$$else,$$

$$Chand.1 = \left(\left(\frac{freq.hs \times composite.fomite \times Trph}{v.decay.min.hand}\right) \times \left(1 - e^{(-v.decay.min.hand\ \times time)}\right)\right) \times (1 - HWeff * prob.hw)^{Freq.HW}$$

In the above equation $freq.hs$ is the frequency of hand to contaminated product box contacts. $Trph$ is the proportion of norovirus transferred from the product box to the susceptible worker's hands per contact. $v.decay.min.hand$ is the inactivation of norovirus particles on the susceptible worker's hands per minute, and *time* is the time of the timestep in minutes. $prob.hw$ is the probability of washing hands, $Freq.HW$ is the frequency of handwashing and $Freq.glove$ is the frequency of glove changes.

### 2.3.3 Viral Dose

The viral dose on the susceptible worker's hands that is transferred to their mouth per timestep, $DT.hh1$ for the first timestep, depends on whether the worker is wearing a mask and is determined by the equation:

$$if\ pwsms > 0,$$

$$DT.hh1 = freq.hf.mask \times \left(\frac{finger.sa}{mouth.sa}\right) \times \left((Chand.1 \times hand.sa) + SWh.1\right) \times Trhface \times T \times infectious$$

$$else,$$

$$DT.hh1 = freq.hf \times \left(\frac{finger.sa}{mouthsa}\right) \times \left((Chand.1 \times hand.sa) + SWh.1\right) \times Trhface \times T \times infectious$$

Where $freq.hf.mask$ and $freq.hf$ are the frequency of hand to mouth contacts when the susceptible worker is wearing a mask and not wearing a mask respectively. $finger.sa$ and $mouth.sa$ are the surface area of the workers fingers and mouth respectively. $Trhface$ is the proportion of norovirus transferred from the workers hands to their mouth per hand to face contact. T is the time of the timestep in minutes, and infectious is the number of infectious people in the modeled scenario. The cumulative dose that the susceptible worker is exposed to over the 8-hour shift is calculated by adding the dose transferred to the worker's mouth for each timestep together. The cumulative dose is calculated through a dose response model to obtain the risk of infection for the susceptible worker.

### 2.4 Transmission from a Vomit Event

The infected worker was assumed to work packing products into boxes. The boxes then progress down the production line to the downstream susceptible worker who palletizes the boxes. The infected worker is assumed to experience a projectile vomiting episode at the start of the worker shift. The infected worker is assumed to turn their head and body to face towards the start of the production line (i.e., upstream), with the conveyer belt and products on the conveyer belt on one side of them, and immediately "projectile" vomits. The infectious vomitus contaminates the floor, conveyer belt, products on the conveyer belt, and room's air. The infected worker is assumed to be removed following the vomiting event, the soiled products disposed of, and the floor and conveyer belt are assumed to not be disinfected very well. It is assumed that only a 10% reduction in virus is achieved at baseline. The susceptible worker is then exposed to norovirus contamination during the remainder of their 8-hour shift through ingesting aerosolized infectious vomitus particles and contact with contaminated surfaces. The contaminated surfaces include the conveyer belt, contaminated via the vomitus, and the product boxes, contaminated by infectious aerosolized particles that fallout of the air.

Interventions including handwashing, glove use, and mask use are built into the following equations as "switches". These intervention "switches" can be turned "on" or "off" to model the use of interventions and determine intervention effectives at reducing the risk of infection

**2.4.1 Aerosol Transmission Modeling**

The following aerosol transport model was leveraged from several SARS-CoV-2 risk assessment models [79, 80]. The source of infectious virus released into the production room was from the sudden onset of an infected worker's projectile vomiting (described above in 2.4), with total viral shedding, $nvAMTvom,$ calculated from the concentration of norovirus in vomitus, $nvV$, times the volume of vomitus expelled $volV$:

$$nvAMTvom = nvV \times volV$$

The proportion of expelled infectious vomitus that was aerosolized, $nvAMTaero$, during projectile vomiting was determined as follows, where $pctaero$ is the percent of vomitus that is aerosolized:

$nvAMTaero = nvAMTvom \times pctaero$

The initial concentration of norovirus particles in the air following the projectile vomiting event is calculated as follows:

$$Ct = \left(\frac{1}{V.loss}\right) \times \left(1 - exp^{\left((-V.loss \times \Delta t)/_{facility.volume}\right)}\right) \times \frac{nvAMTaero}{\Delta t}$$

Where $V.loss$ is the room air exchange rate, $\Delta t$ is the length of the timestep in seconds, and $facility.volume$ is the volume of the production room. It is assumed that viral particles fall out onto surfaces in the production room including product boxes leading to fomite mediated transmission. The amount of virus that falls out at each timestep is calculated as follows:

$$fallout = totalCt \times v.us \times S.us \times \Delta t$$

Where $v.us$ is the deposition velocity and $S.us$ is the surface area of the production room. $totalCt$ is the amount of norovirus in the air during the timestep. $totalCt$ calculated as the amount of virus that remained in the air at the end of the prior timestep times the amount of virus that is lost due to air exchange during the current timestep. For the second timestep, $totalCt2$, and all subsequent timesteps the amount of virus remaining in the air is calculated as follows:

$$totalCt2 = \left(totalCt1 - \left(\frac{fallout1}{facility.volume}\right)\right) \times \left(exp^{\left((-V.loss \times \Delta t)/_{facility.volume}\right)}\right)$$

The amount of virus that is available to be ingested from the air by the susceptible worker during a time step is calculated as the amount of norovirus in the area during the timestep, $totalCt$, minus the amount of virus that fallouts during the timestep over the facility volume:

$$inhaleCt = totalCt - \left(\frac{fallout}{facility.volume}\right)$$

The viral dose, attributed to aerosol mediated transmission, that the susceptible worker ingests during each timestep varies depending on whether the susceptible worker is wearing a mask and is calculated as follows:

$$dose = (inhaleCt \times dep \times inhalerate \times exposuretime) \times \big(1 - (pwsms \times s.mask.p)\big)$$

In the above equation, $dep$ is the deposition fraction of infectious virus into the mouth, nose, or conducting airways. $inhalerate$ is the inhalation rate of the susceptible worker, $exposuretime$ is the length of the timestep in hours, $pwsms$ is the probability that the susceptible worker is wearing a mask, and $s.mask.p$ is the precent reduction in virus ingestion attributed the use of a surgical face mask. The cumulative dose, attributed to aerosol mediated transmission, for the 8-hour work shift was calculated by summing the dose from each timestep.

### 2.4.2 Fomite Transmission Modeling

Viral contamination on the conveyer belt and fallout of aerosolized vomitus serve as reservoirs for fomite mediated transmission. The amount of virus that remains on the conveyer belt after disinfection, $AMTnv.belt,$ is calculated as shown below:

$$AMTnv.belt = (volV.belt \times nvV) \times (1 - clean.eff)$$

Where, $volV.belt$ is the volume of vomitus that lands on the conveyer belt, and $clean.eff$, is the efficacy of disinfection of the conveyer belt. The area of the conveyer belt that was contaminated, $aera.contam$, was assumed based off of simulated vomiting experiments [88]. The concentration of norovirus contamination on the conveyer belt after disinfection was calculated as follows:

$$belt = \left({}^{AMTnv.belt}/_{aera.contam}\right) \times \left({}^{hand.sa}/_{area.belt}\right)$$

Where, $area.belt$ is the surface area of the of the conveyer belt. At the start of each subsequent timestep, 2-8 hours, the concentration of norovirus that remains on the conveyer belt is determined by subtracting the amount of virus that was transferred to the susceptible worker's hand. The amount of norovirus transferred to the susceptible worker's hand varied by whether the susceptible worker changed their gloves:

$$if\ prob.gloves > 0,$$

$$B.hand.1 = \left(\left(\frac{freq.hb \times belt \times Trbh}{v.decay.min.hand}\right) \times \left(1 - e^{(-v.decay.min.hand\ \times time)}\right)\right)$$

$$\times (1 - HWeff * prob.hw)^{Freq.HW} \times (1 - Trhg)^{\ Freq.glove}$$

$$else,$$

$$B.hand.1 = \left(\left(\frac{freq.hb \times belt \times Trbh}{v.decay.min.hand}\right) \times \left(1 - e^{(-v.decay.min.hand\ \times time)}\right)\right)$$

$$\times (1 - HWeff * prob.hw)^{Freq.HW}$$

In the above equations $freq.hb$ is the frequency of hand to conveyer belt contacts, and $Trbh$ is the proportion of norovirus transferred per hand to conveyer belt contact. The susceptible worker also accumulated norovirus contamination on their hands from contacting the product boxes. Product boxes are contaminated by infectious aerosol fallout during each timestep as follows:

$$fomite = \left({}^{fallout}/_{contamcompcartSA}\right) \times \left({}^{hand.sa}/_{compcartonSA}\right)$$

The amount of norovirus contamination that is transferred to the worker's hands from contact with the product boxes during the given timestep, $Chand.1$ for the first timestep, varies by whether the worker changes their gloves during the timestep:

$$if\ prob.gloves > 0,$$

$$Chand.1 = \left(\left(\frac{freq.hs \times fomite1 \times Trph}{v.decay.min.hand}\right) \times \left(1 - e^{(-v.decay.min.hand\ \times time)}\right)\right)$$

$$\times (1 - HWeff * prob.hw)^{Freq.HW} \times (1 - Trhg)^{\ Freq.glove}$$

$$else,$$

$$Chand.1 = \left(\left(\frac{freq.hs \times fomite1 \times Trph}{v.decay.min.hand}\right) \times \left(1 - e^{(-v.decay.min.hand\ \times time)}\right)\right)$$

$$\times (1 - HWeff * prob.hw)^{Freq.HW}$$

The viral dose, attributed to fomite mediated transmission, on the susceptible worker's hands that is transferred to their mouth per timestep, $DT.hh1$, depends on whether the worker is wearing a mask and is determined by the equation:

$$if\ pwsms > 0,$$

$$DT.hh1 = freq.hf.mask \times hand.sa\ \times \left(\frac{finger.sa}{mouth.sa}\right) \times (B.hand.1 + Chand.1) \times Trhface$$

$$\times T \times infectious$$

$$else,$$

$$DT.hh1 = freq.hf \times hand.sa \times \left(\frac{finger.sa}{mouth.sa}\right) \times (B.hand.1 + Chand.1) \times Trhface \times T$$

$$\times infectious$$

The fomite mediated dose that the susceptible worker is exposed to over the 8-hour shift is calculated by adding the dose transferred to the workers mouth for each timestep together. The cumulative dose for the vomit event scenario is calculated by adding the doses from both the aerosol and fomite mediated transmission together. The cumulative dose is then calculated through a dose response model to derive the risk of infection for the susceptible worker.

**2.5 Interventions**

Interventions utilized in the fecal event and vomit event modules included handwashing, glove use, surface cleaning, and mask use. All interventions are coded as “switches” that can be turned “on” or “off” in the code depending on the scenario being modeled. When “switches” are “off”, the probability that the intervention is used is 0 and no reduction in virus is implemented in the calculations to determine the viral dose. When the switches are “on” the probability that the intervention is used is 1 leading to a percent reduction in virus attributed to the specific intervention being modeled. In the vomit event scenario, surface cleaning is modeled at baseline as a 10% reduction in the viral contamination. In the vomit event scenario, when the intervention switch for surface cleaning is turned on, modeling more through disinfection, a 90% reduction (1 $log_{10}$ reduction) in viral contamination is implemented (enhanced efficacy of surface disinfection). In the fecal event scenario and in the vomit event aerosol-fomite mediated transmission pathway, mask use is modeled as a reduction of the in frequency of hand to mouth contacts when the intervention is turned “on” [117]. For the vomit event aerosol mediated transmission pathway, mask use is modeled as the percent reduction in virus ingestion attributed the use of a surgical face mask [114]. The ability to turn interventions on and off allows for the evaluation of each intervention as well as their combined effect on reducing the infection risk.

Interventions were selected based on the FDA's Food Safety and Modernization Act Produce Rule for hand washing, glove use compliance and surface disinfection guidelines for mitigating worker infection risk [45, 46, 71]. The hand washing efficacy was defined as a percent reduction of up to 99.9999% reduction (6 $\log_{10}$ reduction) with the frequency of handwashing defined as one cleaning event per timestep [72, 73]. A low (1-2 $\log_{10}$ reduction) and high (2-6 $\log_{10}$ reduction) handwashing efficacy were modeled. The frequency of glove changes was also defined as one exchange event per timestep. Surface disinfections, in the fecal event scenario, resulted in up to a 99% reduction (2 $\log_{10}$ reduction) and was evaluated at a frequency of every 2 hours to once per shift [72].

**2.6 Risk Assessment**

The viral dose that the susceptible work is exposed to in the fecal and vomit modules was used in the following dose response model to obtain the risk of infection from each exposure event.

$$risk = P \times (1 - exp^{(-dose/_{mu})}$$

Where $P$ is probability of infection, $mu$ is the mean aggregated size, $dose$ is the dose that the susceptible worker is exposure to from the specific transmission pathway [118].

**2.7 Sensitivity Analysis**

A sensitivity analysis was conducted over 10,000 simulations to determine the most influential parameters in estimating the risk of norovirus infection for a susceptible worker. The parameters identified as being most influential in the risk estimate were reported as Spearman rank correlational coefficients using the "tornado" function in the mc2d R package [92].

**3. Modeling Results**

A quantitative microbial risk assessment model (QMRA) was developed in R to evaluate the risk of norovirus infection among food production workers. Model parameters were identified through an extensive literature review including empirical, clinical, and modeling studies (Table 1). Two exposure events, a fecal event module and a projectile vomiting event module, and two routes of transmission, fomite and aerosol mediated transmission, were evaluated (Figure 1). The impact of various mitigation measures including handwashing, glove utilization, surface disinfection, and face mask use were assessed individually and in combination to determine their effectiveness at reducing norovirus infection risk. Finally, a sensitivity analysis was conducted to assess the accumulation of variability across model iterations.

**3.1 Risk of Infection in Fecal Event Module**

Since norovirus outbreaks have been traced back to contamination in the food production setting due to the presence of multiple infected workers, it is important to understand the risk of norovirus infection in the food production setting and how to prevent infections in the food production setting [20]. One mode of doing so is understanding the risk of infection posed by different exposure events and transmission pathways. To determine the infection risk posed by an infected food production worker experiencing repeated fecal events, we modeled an 8-hour cumulative exposure to infectious fecal matter via fomite mediated transmission for a susceptible worker. The fomite-mediated infection risk was 0.223 ($5^{th}$-$95^{th}$ percentile: 0.009, 0.716), after 8 hours of exposure (Figure 2A). These results suggest that the presence of a single infected worker poses a 22% risk of infection via fomite mediated transmission of infectious fecal matter to a susceptible worker.

### 3.2 Risk of Infection in Vomit Event Module

Individuals infected with norovirus may experience sudden onset of projectile vomiting with little to no warning [10, 66, 119]. To understand the infection risk posed by an infected food production worker who experiences a projectile vomiting event, we modeled the aerosol and aerosol-contaminated fomite-mediated infection risk associated with an 8-hour cumulative exposure. The risk of infection from ingesting aerosolized viral particles alone was determined to be $8.2\times10^{-4}$ ($5^{th}$-$95^{th}$ percentile:$5.5\times10^{-5}$, $1.9\times10^{-2}$), while the aerosol-fomite mediated infection risk was $4.1\times10^{-3}$ ($5^{th}$-$95^{th}$ percentile: $2.0\times10^{-4}$, $1.2\times10^{-1}$), producing a combined aerosol and fomite-mediated infection risk of $5.3\times10^{-3}$ ($5^{th}$-$95^{th}$ percentile: $2.9\times10^{-4}$, $1.4\times10^{-1}$) (Figure 2B). These results suggested that aerosol-fomite mediated transmission, compared to aerosol mediated transmission, accounts for a greater portion of the risk of infection attributed to exposure to a projectile vomiting event along the production line.

### 3.3 Effects of Hand Hygiene Interventions on Reducing Infection Risk

Proper handwashing and glove use are known to reduce the spread and direct skin contact with norovirus [24, 51, 120]. To quantify the impact handwashing and glove compliance have on decreasing the infection risk within each exposure event scenario, the baseline risk was compared to the risk attributed to low efficacy handwashing (1-2 $\log_{10}$ reduction per event), high efficacy handwashing (2-6 $\log_{10}$ reduction per event), glove use only, or a combination of handwashing and glove use as discussed in methods section 2.5. In the fecal event scenario, the percent reduction attributed to low efficacy (1-2 $log_{10}$ reduction per event) handwashing only was 2.64%, 16.25% for high handwashing efficacy (2-6 $log_{10}$ reduction per event), 2.30% for glove use, 2.76% for low handwashing efficacy and glove use, and 16.26% for high handwashing efficacy and glove use (Figure 3A). In the vomit event scenario, the percent reduction attributed to low efficacy handwashing only was 78.65%, 84.07% for high efficacy handwashing, 17.76% for glove use, 79.83% for low handwashing efficacy and glove use, and 84.15% for high handwashing efficacy and glove use (Figure 3B). These findings indicate that hand hygiene interventions were more impactful in the vomit event scenario than in the fecal event scenario.

### 3.4 Effects of Surface Disinfection on Reducing Infection Risk

Surface disinfection practices are recommended during food preparation to reduce the risk of foodborne illness from pathogens such as norovirus [51, 121]. To understand the impact of surface disinfection on reducing the risk of norovirus infection, the baseline risk was compared to increasing the frequency of disinfection in the fecal event scenario and improved surface disinfection of the conveyer belt from 10% (baseline) reduction in total norovirus contamination during removal of vomitus to 90% (enhanced efficacy of surface disinfection) reduction in total norovirus contamination during removal of vomitus. The methods section provides additional information on the assumptions made and the values used for surface disinfection (methods sections 2.1, 2.4, 2.5). For the fecal event scenario relative to no surface disinfection, the impact of disinfection event frequency once, every four hours, or every two hours was evaluated. The percent reduction in the infection risk was, 42.29% for disinfection once per shift, 91.05% for disinfection every four hours, and 91.22% disinfection every two hours (Figure 4A). In the vomit scenario, improved disinfection efficacy of the conveyer belt resulted in an 72.69% reduction in the infection risk compared to baseline (Figure 4B). These results indicate that surface disinfection was an effective means to reduces the risk of norovirus infection for the susceptible worker across both exposure scenarios.

### 3.5 Effects of Surgical Face Mask Use on Reducing Infection Risk

It has been reported that during the current COVID-19 pandemic there has been a 49% reduction in norovirus outbreaks [86]. It has been proposed that this reduction in outbreaks could be in part attributed to mask use, among other interventions. To evaluate how much masks can reduce the risk of infection, mask use was modeled as a 73% decrease in the number of hand to face contacts for the fomite mediated and aerosol-fomite mediated transmission pathways [117]. For the aerosol transmission pathway, mask use was modeled as a 37-99.8% percent reduction in the amount of norovirus taken into the mouth, nose, or conducting airways [114, 115]. In the fecal event scenario, mask use resulted in a 69.25% reduction in the risk of infection (Figure 5A). While in in the vomit scenario there was a 72.22% reduction in the risk of infection attributed to mask use (Figure 5B). These results suggest that masks are an effective means of reducing the risk of infection both through decreased hand to face contacts as well as reduced aerosol ingestion of norovirus particles.

### 3.6 Effects of Combination Intervention Utilization on Reducing Infection Risk

While each intervention alone reduced the risk of infection, to varying degrees, in practice, multiple interventions are often utilized together in the food production facility. The baseline exposure scenarios, for the fecal and vomit event modules, were compared to the use of combined interventions to determine the combined effect of the interventions on reducing the risk of infection. In the fecal event scenario, when high handwashing efficacy, glove use, surface disinfection every four hours, and mask use were utilized together a 98.78% reduction in the risk of infection was achieved (Figure 6A). Similarly, in the vomit event scenario, a 96.08% reduction in the risk of infection was achieved when high handwashing efficacy, glove use, increased efficacy of surface disinfection of the conveyer belt, and mask use were used in combination (Figure 6B). As would be expected, these results confirm that multiple intervention utilization provides a greater level of protection, compared to individual intervention use, from norovirus infection for the susceptible worker.

**3.7 Sensitivity Analysis**

Spearman rank correlation coefficients were calculated to identify the parameters that were most influential in the cumulative norovirus infection risk estimate from both the fecal event and vomit event modules. In the fecal event module, the parameters identified as increasing the risk of norovirus infection were the concentration of norovirus in feces (rho= 0.57), and the mass of feces per hand (rho= 0.53). In the fecal event module, the parameter identified as decreasing the risk of norovirus infection the most was the surface disinfection efficacy (rho= -0.30) (Figure 7). In the vomit event module, the parameters identified as increasing the risk of norovirus infection were the concentration of norovirus in vomit (rho= 0.97), and the deposition of virus into the mouth, nose and conducting airways (rho= 0.15). In the vomit event module, the parameter identified as decreasing the risk of norovirus infection the most was handwashing efficacy (rho= -0.01) (Figure 8). These results suggest that the propagation of variability attributed to parameter heterogeneity was greatest for norovirus viral load parameters in model modeled scenarios.

## 4. Discussion

The goal of this study was to identify the cumulative infection risk associated with specific exposure events (fecal and vomit) and associated transmission pathways (fomite and aerosol) on the food production floor. Additionally, we aimed to quantify the impact of mitigation measures on the risk of norovirus infection among susceptible food production floor workers. Overall, these results demonstrate that the risk of norovirus infection varies by exposure event and associated transmission pathways. Furthermore, the risk of norovirus infection across both exposure events, and simulated transmission pathways, was reduced by the utilization of various interventions. The greatest reduction in the risk of infection to the susceptible worker was observed when multiple interventions were applied in combination (handwashing, gloving, surface disinfection, and mask use). These results provide insight into the risk of norovirus infection for food production workers for two exposure events as well as reinforces the importance and effectiveness of infection risk reduction measures.

### 4.1 Risk of Norovirus Infection Differs by Exposure Event and Transmission Pathways

Our model indicated that the simulated fecal event exposure module posed a greater baseline risk of infection (0.22 infection risk) than the simulated vomit event exposure module (0.0053 infection risk). One hypothesis to explain these results is that there is a different amount of norovirus contamination accrued in each exposure scenario. The fecal event scenario simulated repeated fecal events, a total of four fecal events were simulated, over the 8-hour shift leading to increasing and cumulative contamination of fomite reservoirs (bathroom environment, production floor door handle). The vomit event scenario, however, simulated a single projectile vomiting event, for which less than 0.03% of vomitus was aerosolized and a maximum of 25%

of vomitus landed on the conveyer belt contributing to fomite mediated transmission. Our finding of a greater risk of infection from exposure to contamination from fecal events, compared to the vomit event, is consistent with the findings of Overbey et al. [122]. The norovirus QMRA model created by Overbey et al. found that fomite contact risk estimates, for hospital environmental services workers, attributed to vomit events, were four orders of magnitude lower than fomite contact risk estimates attributed to fecal events. These results were also attributed to reduced viral exposure from vomit events. Another norovirus QMRA study, by Duret et al., also found that aerosol contamination, of the restroom environment, was less important than contamination from direct hand contact with fomites [49].

For the vomit event scenario, our model found that the risk of infection for a susceptible food production worker attributed to aerosol mediated transmission was 0.00082 while the infection risk attributed aerosol-fomite mediated transmission was 0.0041(80% greater than aerosol mediated transmission). Aerosol mediated transmission refers to the ingestion of aerosolized infectious vomitus particles from the air. In contrast, aerosol-fomite mediated transmission refers to contact with surfaces that have been contaminated by deposition of aerosolized infectious vomitus particles on to the surfaces as well as contamination from vomitus that lands on the surface leading to fomite mediated transmission of norovirus. For our vomit event scenario, it is likely that the risk attributed to aerosol mediated transmission is so small because the proportion of norovirus that was aerosolized was less than 0.03% of norovirus in the vomit. Based on our results for the vomit event scenario it appears that aerosol-fomite mediated transmission drives the risk of infection from exposure to a vomit event. At the time of this writing, there are no norovirus QMRA studies to compare our vomit event scenario results to as this is the first norovirus QMRA model to incorporate aerosol mediated transmission from exposure to a vomit event.

### 4.1.1 Risk of Norovirus Infection from Exposure to Repeated Fecal Events

As previously mentioned, the fecal event module identified a 22% risk of infection for a susceptible worker in the absence of interventions. Several factors could be contributing to this risk of infection, including the level of viral shedding simulated (maximum 8 $\log_{10}$ infectious viral particles per gram of feces), and the low infectious dose of norovirus [33]. Overbey et al. simulated slightly higher fecal norovirus viral shedding level (maximum 10 $\log_{10}$ infectious viral particles) and obtained a similar, but slightly larger, risk of infection of 33% for a susceptible worker not utilizing protective measures [122]. Furthermore the baseline results obtained for the fecal event module are reasonable as our model resulted in a dose of over $10^3$ genomic equivalent copies (GEC) of norovirus, ingested by the susceptible worker, and human challenge studies have found that approximately 33% of people who receive an inoculum of ~$10^3$ GEC of norovirus will become infected [33].

### 4.1.2 Risk of Norovirus Infection from a Vomit Exposure Event

Contrary to previously reported findings [123], our model identified a low risk of norovirus infection from exposure to a single projectile vomiting event in the food production setting. A study by Adams et al. found that vomiting norovirus-infected individuals infected 2.12 times the number of individuals compared to non-vomiting norovirus-infected individuals [123]. Another report of a norovirus outbreak, caused by a restaurant patron who experienced a vomiting episode, attributed subsequent infections to exposure to aerosolized virus from the vomiting event [66]. One reason for our divergent findings is that the infected worker in our model is removed immediately after a single vomiting event. In contrast, the study by Adams et al. took place in long term care facilities in which individuals were continually exposed to the infected individual as well as to multiple modes of transmission [123]. Another mechanism that may account for the difference in results is that our model simulated a situation in which the susceptible worker was distanced from the infected worker and never exposed to droplet spray from the vomiting event. In the reported restaurant outbreak, subsequent cases were in close contact with the infected individual eating at the same or nearby tables [66]. As previously mentioned, our model is the first to simulate the risk from aerosol mediated transmission to a susceptible worker. Previous norovirus QMRA models have quantified the aerosol-fomite mediated risk of infection to susceptible individuals, the risk from which was low. However, the risk from ingestion of aerosolized particles was not investigated [49, 122].

### 4.2 Risk of Norovirus Infection is Reduced Differentially by Intervention Type

Findings from our model demonstrate the importance of infection mitigation measures for reducing the risk of norovirus infection across both exposure events (fecal, vomit) and associated transmission pathways (fomite, aerosol). Interventions that align with the existing Food Safety Modernization Act (FSMA) requirements, including hand hygiene interventions (handwashing, glove use) and surface disinfection were evaluated [45, 46, 71]. Surgical mask use was also modeled to understand how this intervention might reduce the risk of norovirus infection given its continued use and central role as a mitigation measure throughout the COVID-19 pandemic [124, 125]. Individual intervention effectiveness varied across the modeled exposure events with certain interventions proving more effective than others.

Hand hygiene interventions proved minimally effective in the fecal exposure event scenario. The maximum reduction in infection risk achieved, in the fecal module, was for the combined use of handwashing and gloving which resulted in a risk reduction of 16%. Our lower effectiveness of hand hygiene interventions for the fecal event module is due to the high fomite contamination resulting from repeated fecal events (1311 GEC of norovirus without any interventions) and contamination of the fomite reservoir (restroom environment and production floor door handle). Handwashing by the susceptible worker only occurs the in the restroom environment. Therefore, subsequent contact with fomite reservoirs by the susceptible worker, outside the restroom, leads to renewed accumulation of norovirus contamination. With high levels of contamination accumulation on the susceptible workers hands from contact with the fomite reservoirs, a dose of 1066 GEC of norovirus is still achieved in the presence of handwashing (2-6 $log_{10}$ reduction) and gloving, only in the restroom enviroment. This dose (1066 GEC of norovirus) explains the resulting 19% risk of infection for the susceptible worker and minimal effectiveness of the hand hygiene interventions in the fecal event module, especially given that the infectious dose 50 (ID50) of norovirus has been estimated to be as low as 18 virus particles [33]. Thus, these results suggest that for exposure to fecal contamination, hand hygiene interventions (handwashing, glove use) should be paired with other interventions (surface disinfection, masking) to achieve a reduction in the dose of norovirus below the ID50 that a susceptible worker is exposed to.

While the risk of infection in the vomit event module was low at baseline (0.53% infection risk), implementation of mitigation measures is still important to reduce the risk of infection. Hand hygiene interventions in the vomit event module achieved a maximum risk reduction of 84% for handwashing and a maximum risk reduction of 18% for glove use. One reason for only the 18% reduction in the risk of infection for glove use is that our model assumes that 0-44% of norovirus contamination could be transferred from the contaminated hand of the infected or susceptible worker to their gloves during gloving. Work done by Ronnqvist et al. demonstrated the process of transfer of norovirus from norovirus contaminated hands to gloves during donning of clean gloves [100]. The transfer of norovirus from the contaminated hands to gloves during the gloving process explains the minimal efficacy of gloving as a means to reduce the risk of infection for the susceptible worker.

Surface disinfection was an important risk reductions measure across both modeled exposure event scenarios. In the fecal event scenario, surface disinfection of fomite reservoirs proved the most effective individual mitigation measure, achieving maximum risk reduction of 91%. In the vomit event scenario, an enhanced efficacy of surface disinfection was modeled (1 $\log_{10}$ reduction) achieving maximum risk reduction of 73% in the risk of infection. One hypothesis for the reduction in the risk of infection achieved in both scenarios is that mitigation measures, such as surface disinfection, that act to reduce to viral contamination on contact surfaces, result in reduced accumulation viral contamination on the susceptible workers hands. In the fecal event module at baseline 1311 GEC of norovirus accumulate on the susceptible workers hands. This is reduced to 112 GEC of norovirus when surface disinfection is utilized. In the vomit event module at baseline 58 GEC of norovirus accumulate on the susceptible workers hands. This is reduced to 2 GEC of norovirus when surface disinfection is utilized. The ID50 of norovirus has been estimated to be 18 virus particles [33]. Thus, the reduced amount of norovirus contamination on the susceptible workers hands, below the ID50 for the vomit event module, results in a reduced risk of infection for the susceptible worker. Our surface disinfection results are in line with previous QMRA modeling that has also identified surface disinfection as an important measure for reducing the risk of infection by 93% for rotavirus, and 94% for rhinovirus and influenza A virus by reducing the amount of virus on contact surfaces and susceptible individuals hands [126].

Mask use has not previously been evaluated as an intervention for reducing the risk of norovirus infection. The current COVID-19 pandemic has seen the implementation of mask wearing across may settings including the food production setting [127, 128]. Bruggink et al. reported a 49% reduction in norovirus outbreaks in 2020 proposing that interventions implemented in response to the COVID-19 pandemic, such as mask use among other interventions, may have contributed to the reduction in outbreaks [86]. In the fecal event module, face mask use alone resulted in a 69% decrease in the risk of infection. This decrease was attributed to decreased hand to mouth contacts as a result of face mask use. Research conducted by Chen et al. found that mask wearing was associated with reduced face-touching behaviors, specifically reduced touching of the eyes, nose, and mouth [129]. Similarly, in the vomit event module, face mask use alone resulted in a 72% reduction inf the risk of infection. This reduction was attributed both to decreased hand to mouth contacts as well as decreased ingestion of aerosolized virus. Canales et al. reported that the number of hand-to-mouth contacts had the greatest influence on total dose in their norovirus QMRA model evaluating the role of fomites in a norovirus outbreak [130].

As expected, our model confirmed that combined intervention use was most effective at reducing the risk of norovirus infection for a susceptible food production worker. Across both the fecal and vomit exposure event modules, utilization of a combination of handwashing, gloving, surface disinfection, and mask use resulted in a 99% reduction in the risk of infection for the fecal event module and 96% reduction for in the risk of infection for the vomit event module. These results are supported by Mokhtari et al. who found that utilization of multiple interventions (handwashing, glove use) resulted in norovirus contamination control below their cut-off-level of 10 infectious norovirus particles per food serving in a retail food setting [72]. Sobolik et al. identified a similar risk reduction of 99% for combined intervention use (increased handwashing efficacy, handwashing and glove use compliance) in their model evaluating the risk of infection to consumers from consumption of contaminated produce [73]. Given the low infectious dose and high viral shedding of infected individual, multiple interventions should be utilized simultaneously to reduces the risk of transmission and subsequent infection [33].

### 4.4 Modeling Strengths, Limitations, & Future Directions

The model presented here has several strengths. One strength of the model is that we leveraged current findings from the peer-reviewed literature along with expertise from industry partners to generate realistic exposure scenarios and transmission pathways. An additional strength of our model is the consideration of aerosol mediated exposure to norovirus from a vomiting event, something that has not been done until now. Including the aerosol mediated transmission in our model provided a better understanding of the complete risk attributed to exposure to a vomiting event because our model accounted for the modes of transmission from exposure to a vomiting event. Finally, our model is easily adaptable to modeling of either additional exposure pathways in the food production setting or adaption of the current model to different settings such as restaurants or hospitals.

Our model, as is the case with all models, is an abstraction of reality which brings with it inherent limitations. One limitation of our model is that it cannot account for any exposure that might take place outside of the modeled scenarios. For instance, the model cannot account for risk of infection from exposures that may occur in the breakroom environment or after work as these scenarios were not modeled. Additionally, our model does not consider the risk of infection to the individual tasked with cleaning up the vomitus expelled by the infected worker. This task carries an inherent risk of infection that would be important to quantify and understand how to best minimize the infection risk. The Centers for Disease Control and Prevention notes that individuals caring for norovirus infected persons are at risk of infection from contact infectious bodily fluids such as vomitus [28]. In this same vein, our model does not consider the risk of infection to additional food production workers on the production floor who may use the contaminated restroom and contact the contaminated production floor door handle (fecal vent scenario) or be present on the floor during and after the vomit event (vomit event scenario).

Future QMRA models may consider addressing the limitations of the current model, modeling additional interventions (e.g., increased air exchanges, alternative mask types), and evaluating the risk from aerosol mediation transmission in alternative settings (e.g., hospitals, restaurants, cruise ships). Future modeling work should also consider the risk of infection to the worker tasked with cleaning up the vomitus. Future work could also aim to understand how the risk of infection changes when the products contaminated with vomitus, assumed to be disposed of in the current model, are kept and contacted by the susceptible worker. Additional interventions that could be considered by future work in the food production setting include evaluating the effects of increase air exchanges on the risk of infection. As the current model is the only norovirus QMRA model to consider the risk of infection from aerosol and aerosol-fomite mediation transmission, future work should aim to evaluate the risk associated with these transmission pathways in additional settings (e.g., hospitals, restaurants, cruise ships).

**4.5 Conclusions & Public Health Recommendations**

Preventing infection of food production workers is an important step in protecting both workforce health and the integrity of the US food supply. Until this study, modeling work has neglected the risk of norovirus infection to the food production worker, focusing instead on the risk to the consumer. By understanding the risk to the food production worker, we can understand how to reduce the risk of subsequent infections in the food production environment thereby reducing the opportunity for contamination of products and subsequent risk to the consumer.

Our model has identified the risk of norovirus infection to a susceptible food production worker from two different exposure events (fecal, vomit) and associated transmission pathways (fomite, aerosol). We found that exposure to fecal contamination via fomite mediated transmission posed the greatest risk of infection. Exposure to a single projectile vomiting event carried minimal risk of infection to the susceptible food production worker, compared to exposure to norovirus contamination from repeated fecal events. For individual intervention use, surface disinfection proved particularly important for reducing the risk of infection from exposure to fecal contamination, while handwashing provided the greatest risk reduction for exposure to contamination from vomitus. Across both modeled exposure events, combined intervention use (handwashing, gloving, surface disinfection, mask use) was the most effective intervention for reducing the risk of infection.

Our findings highlight the importance of utilizing a set of interventions in the food production environment. Food production facilities should continue to follow FSMA requirements for handwashing and surface disinfection. Based on our results, handwashing should be emphasized after exposure to vomiting events and surface disinfection should be emphasized after fecal events as these individual interventions resulted in the greatest reduction in the risk of infection. Continued mask use, even after the COVID-19 pandemic, if not standard practice, should be implemented in the food production setting as this intervention provides substantial protection from both exposure events and evaluated transmission pathways. In conclusion, by leveraging multiple interventions the risk from different norovirus exposure events can be effectively mitigated thereby protect worker health and maintain the US food supply.

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## 6. Tables and Figures

**Table 1. Parameters, values, and probability distributions used in the QMRA models.**

| Variable Notation | Units | Description | Input Values | Distribution | References |
|---|---|---|---|---|---|
| **Inputs associated with norovirus viral load and contamination of surfaces, room air, and worker hands with infectious fecal matter or vomitus** | | | | | |
| nvf | Virions/gram | Concentration of norovirus in feces [virions/gram] | min= 100, mode= 1,000,000, max= 100,000,000, (shape = 10) | Beta-Pert | [49, 50, 72, 94, 131, 132] |
| mfh | grams/hand | Mass of feces/hand | min=0.00000001, mode=0.0001, max=0.1 | Triangle | [76] |
| IW.Br | count | Number of defecations per shift | 4 | Point estimate | [49, 72, 116] |
| nvV | log10(virions)/mL | Concentration of norovirus in vomit | min=3, mode=4.5, max=7 | Beta-Pert | [49, 93, 95] |
| volV | mL | Volume of vomit expelled | min= 200, mode=500, max=800 | Triangle | [88, 96] |

| | | | | | |
|---|---|---|---|---|---|
| NumV | count | Number of vomit events per-shift | 1 | Point estimate | Assumed |
| pctaero | proportion | percent aerosolization of total virus vomited | 0.03% | Point estimate | [96] |
| dpa | cm | particle size | min = 0.000095, mode=0.000178, max = 0.000451 | Triangle | [68] |
| vs | m/s | settling velocity for a single NoV particle | 4.7 x 10^−8 | Point estimate | [96] |
| dep | Proportion | Deposition fraction of virus into the mouth, nose, and conducting airways | min = 0.1, max = 0.3 | Uniform | [68] |
| inhalerate | $m^3$/hour | Inhalation rate per hour | min=1.62, max=3.18 | Uniform | [133] |

| | | | | | |
|---|---|---|---|---|---|
| Trhg | Proportion | Proportion of norovirus transfer per touch from contaminated bare hand to glove | min=0, max=0.44 | Uniform | [100] |
| Trhdoor | Proportion | transfer from hand or glove to door handle | min=0.094, max=0.166 | Uniform | [97-99, 101, 134] |
| Trdoorh | Proportion | transfer from door handle to hand or glove | min=0.051, max=0.089 | Uniform | [97-99, 101, 134] |
| Trhp | Proportion | transfer from hand or glove to package | min=0.37, mode=0.53, max =0.69 | Triangle | [101] |
| Trph | Proportion | transfer from package to hand or glove | min=0.14, mode=0.20, max =0.26 | Triangle | [101] |

| | | | | | |
|---|---|---|---|---|---|
| Trhbr | Proportion | Transfer from hands to restroom environment | min=0.001, mode=0.13, max=0.27 | Triangle | [97] |
| Trbr | Proportion | Transfer from restroom environment to hands | min=0.036, mode=0.07, max=0.22 | Triangle | [97] |
| Trbh | Proportion | Transfer from conveyor belt to hands or gloves | min=0.036, mode=0.07, max=0.22 | Triangle | [97] |
| Trhface | Proportion | Transfer from hand to face | min=0.137, mode = 0.20, max = 0.263 | Triangle | [102] |
| decayH | $Minute^{-1}$ | Inactivation of particles on hands per minute | min=0, max=0.01783 | Uniform | [134] |
| decayDr | $Minute^{-1}$ | Inactivation of particles on door handle per minute | min=0.00002, max=0.0096 | Uniform | [134] |

**Inputs associated with worker health and hygiene behavior (handwashing compliance and efficacy, glove use, surface disinfection, mask use)**

| | | | | | |
|---|---|---|---|---|---|
| hweff | % reduction | Handwashing removal efficacy | min=.90, mode=0.96, max=0.99 or min=.99, mode=0.9999, max=0.999999 | Triangle | [72, 103-112] |
| Freq.hw | HW/hour | Frequency of handwashing per hour | 1 | Point estimate | Assumed |
| Freq.glove | Glove/hour | Frequency of glove changes per hour | 1 | Point estimate | Assumed |
| sc.eff.p | % reduction | Surface disinfection of door handle in fecal scenario | min=0.9, max=0.99 | Uniform | [90] |

| | | | | | |
|---|---|---|---|---|---|
| clean.eff | % reduction | Surface disinfection of conveyor belt in vomit scenario | Baseline: 10% Intervention: 90% | Point estimate | Assumed |
| s.mask.p | % reduction | Susceptible worker surgical mask efficacy vomit scenario | min=0.37, max=0.998 | Uniform | [114, 115] |
| **Inputs associated with dose-response and risk characterization for the susceptible worker** | | | | | |
| μ | | Mean aggregate size | min=399, mode=1106, max=2428 | Triangle | [118] |
| P | | Dose-response: probability of infection among susceptible subjects | min=0.63, mode=0.722, max=0.8 | Triangle | [118] |

**Figure 1. Norovirus QMRA schematic for fecal and vomit exposure pathways**

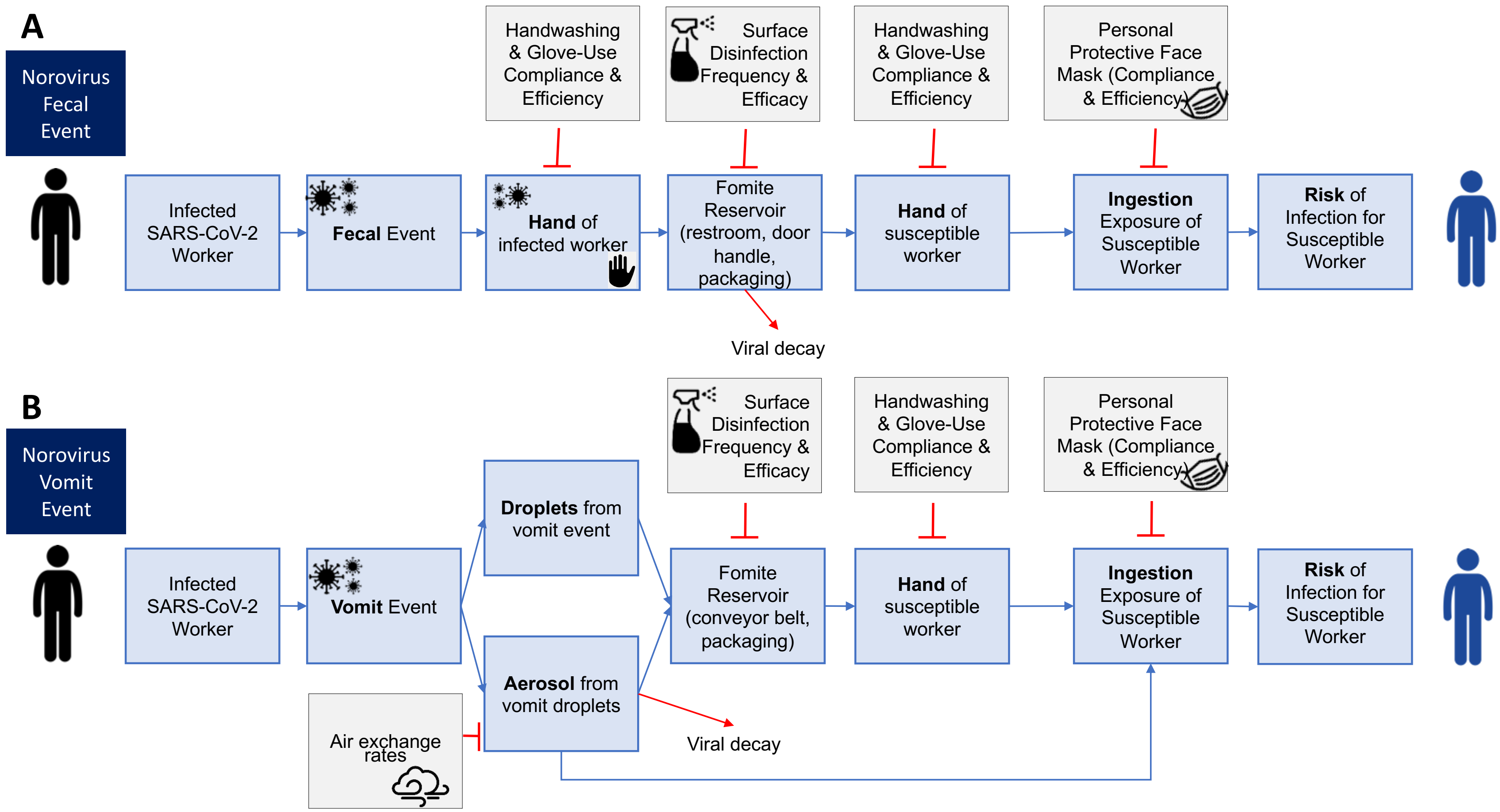


**Figure 1.** Norovirus QMRA schematic for (A) fecal and (B) vomit events to assess infection risk from fomite (fecal and vomit events) and aerosol (vomit event) transmission pathways. The steps of each transmission pathway from infected worker (black person on left) to susceptible worker (blue person on right) are displayed in the blue boxes with the blue arrows indicating the flow from one step to the next. Mitigation measures (hand hygiene, surface disinfection, masking, air exchange) acting at various points along the exposure pathway are depicted in the gray boxes with the red connectors indicating at which step they are implemented. The red arrows represent the viral decay that occurs at the specified step in the transmission pathway.

**Figure 2. Risk of norovirus infection across two modeled exposure pathways.**

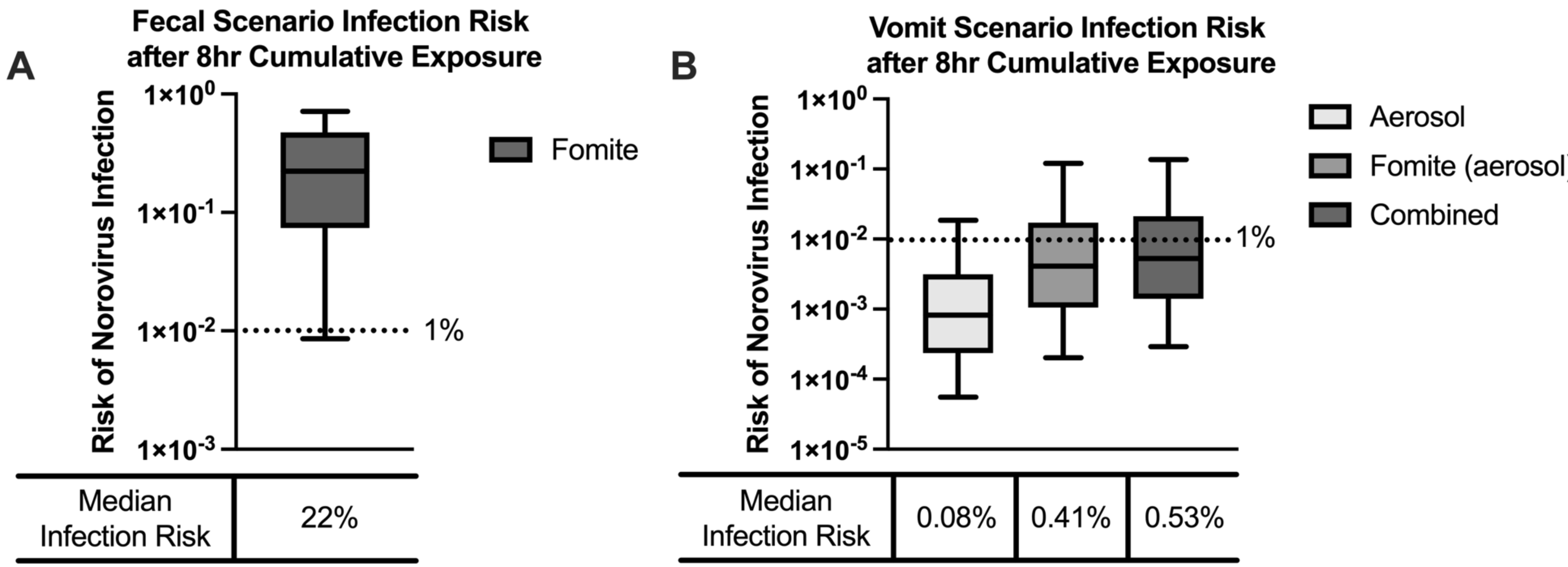


**Figure 2. Risk of norovirus infection varies across transmission route (aerosol, fomite-mediated).** The Y-axis represents the risk of norovirus infection for a susceptible worker downstream of an individual infected worker on the production line who experiences a (A) fecal event or a (B) vomit event. Each norovirus transmission pathway assessed per modeled scenario is listed in the legend to the right and represented by each boxplot. Boxplots display the 5th and 95th percentiles (whiskers), 25th and 75th percentiles (boxes), and median (middle line) risk of infection. Below each boxplot is the median infection risk.

**Figure 3. Reduction in norovirus infection risk attributed to hand hygiene interventions**

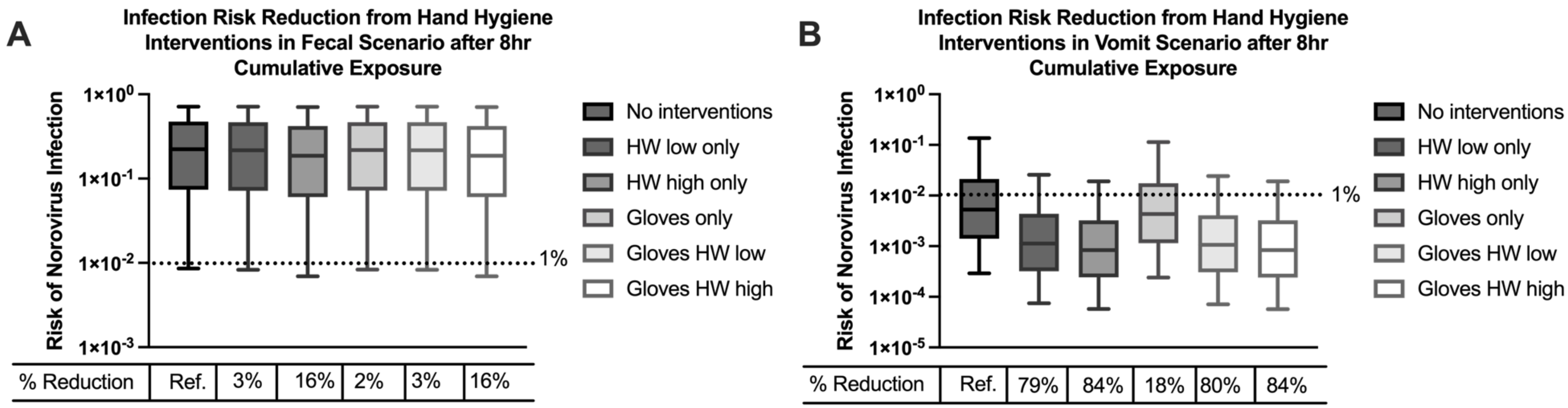


**Figure 3. Reduction in norovirus infection risk attributed to hand hygiene interventions (handwashing practices, glove utilization, or both) varies by intervention type.** The Y-axis represents the risk of norovirus infection for a susceptible worker downstream of an individual infected worker on the production line who experiences a (A) fecal event or a (B) vomit event. The darkest boxplot represents no interventions, and each subsequent boxplot represents the cumulative risk of infection after hand hygiene intervention implementation. Boxplots display the 5$^{th}$ and 95$^{th}$ percentiles (whiskers), 25$^{th}$ and 75$^{th}$ percentiles (boxes), and median (middle line) risk of infection. Below each boxplot is the percentage infection risk reduction attributed to each intervention.

**Figure 4. Reduction in norovirus infection risk attributed to surface disinfection**

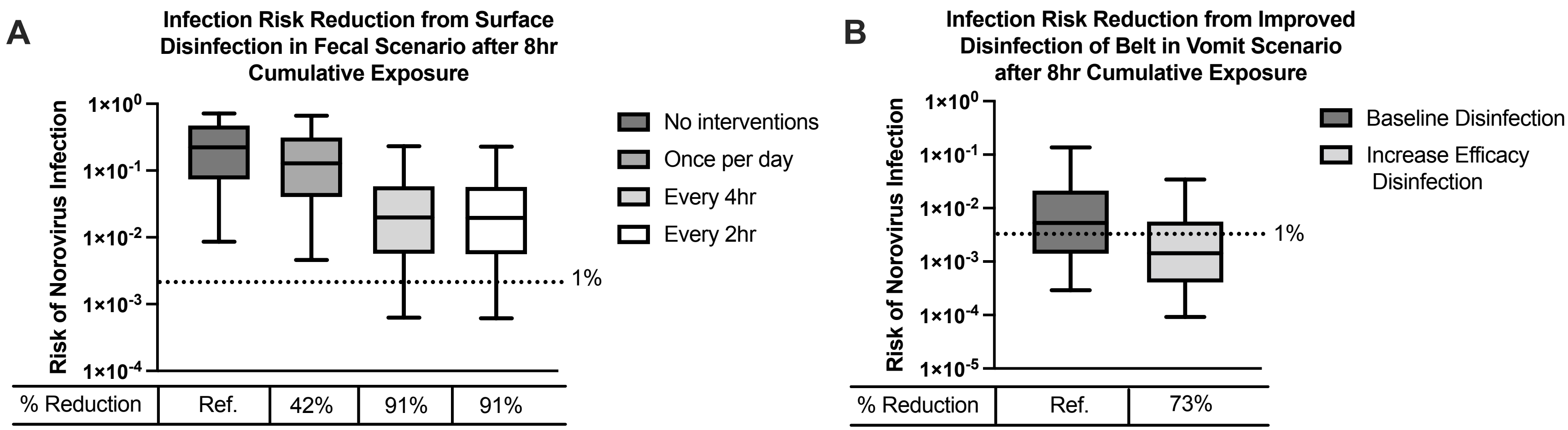


**Figure 4. Reduction in norovirus infection risk attributed to surface disinfection variers by frequency (daily, every 4 hours, every 2 hours). and efficacy** The Y-axis represents the risk of norovirus infection for a susceptible worker downstream of an individual infected worker on the production line who experiences a (A) fecal event or a (B) vomit event. The darkest boxplot represents the cumulative risk infection without interventions and each subsequent boxplot represents the cumulative risk of infection after surface disinfection. The frequency of surface disinfection for (A) is listed in the legend to the right for and represented by each boxplot. For (B) Baseline Disinfection represents a 10% reduction in total norovirus contamination while Increased Efficacy Disinfection represents a 90% reduction in total norovirus contamination. Boxplots display the 5$^{th}$ and 95$^{th}$ percentiles (whiskers), 25$^{th}$ and 75$^{th}$ percentiles (boxes), and median (middle line) risk of infection. Below each boxplot is the percentage infection risk reduction attributed to each frequency or increased efficacy of surface disinfection.

**Figure 5. Reduction in norovirus infection risk attributed to use of a surgical face mask**

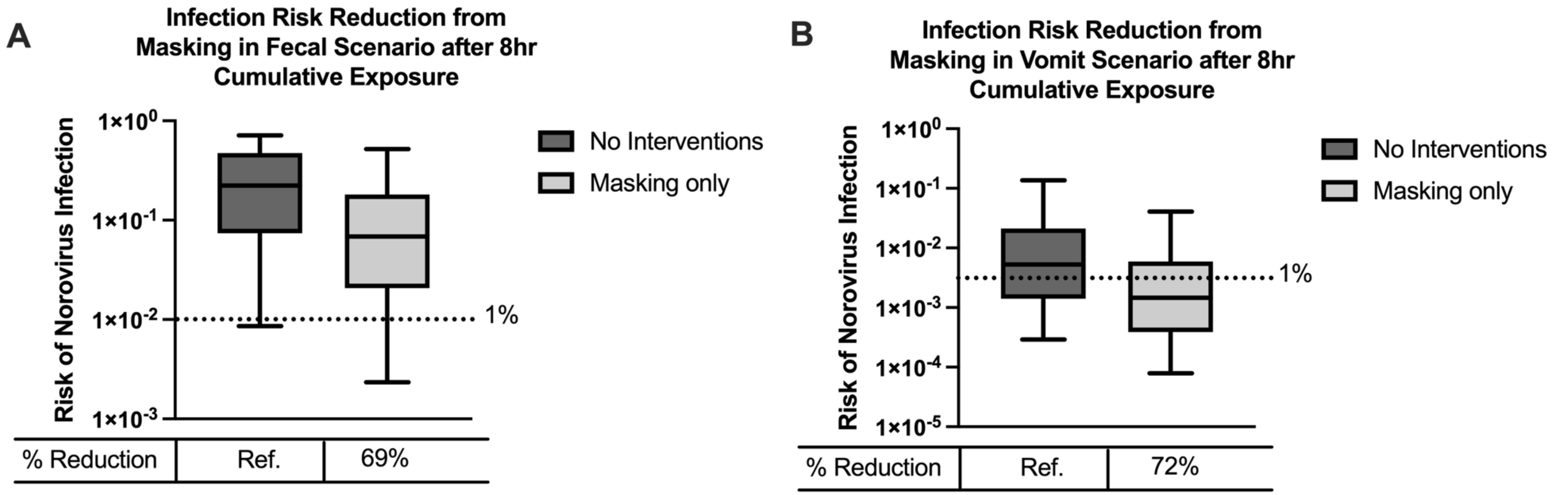


**Figure 5. Reduction in norovirus infection risk attributed to surgical face mask wearing by the susceptible worker per modeled scenario.** The Y-axis represents the risk of norovirus infection for a susceptible worker downstream of an individual infected worker on the production line who experiences a (A) fecal event or a (B) vomit event. For each panel, the darkest boxplot represents the cumulative risk of infection without any interventions, while the lightest boxplot representing the cumulative risk of infection for a susceptible working wearing a surgical face mask. Boxplots display the 5$^{th}$ and 95$^{th}$ percentiles (whiskers), 25$^{th}$ and 75$^{th}$ percentiles (boxes), and median (middle line) risk of infection. Below each boxplot is the percentage infection risk reduction attributed to wearing a surgical grade face mask.

**Figure 6. Reduction in norovirus infection risk attributed to use of combined interventions**

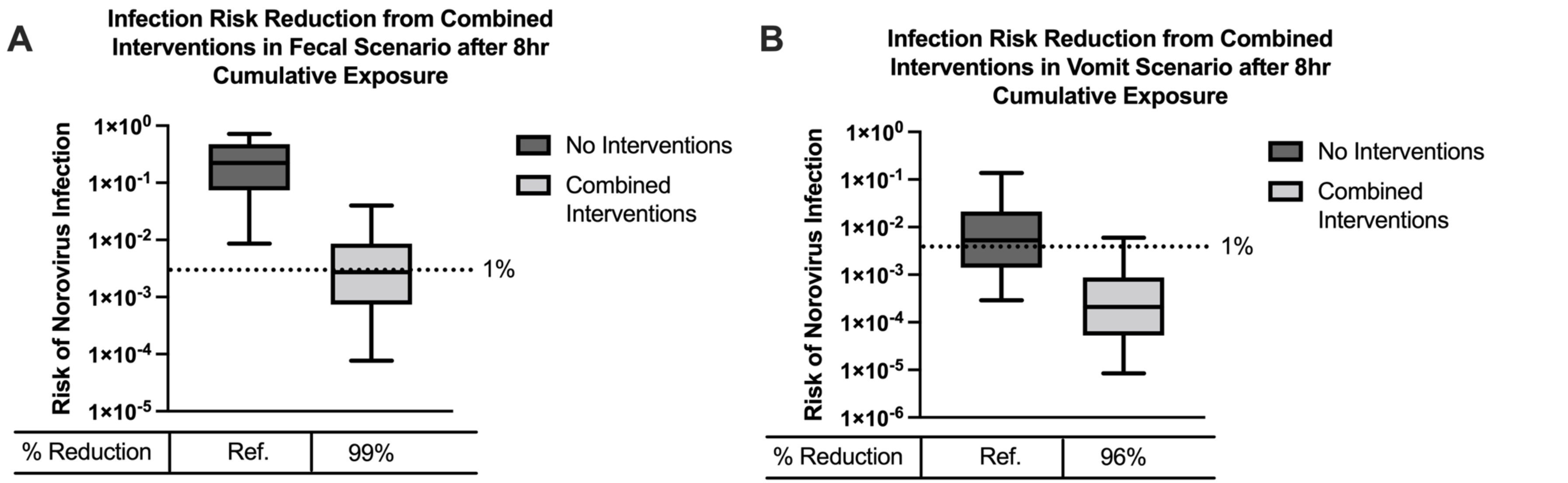


**Figure 6. Reduction in norovirus infection risk attributed to combined intervention use by the susceptible worker per modeled scenario.** The Y-axis represents the risk of norovirus infection for a susceptible worker downstream of an individual infected worker on the production line who experiences a (A) fecal event or a (B) vomit event. For each panel, the darkest boxplot represents the cumulative risk of infection without any interventions, while the lightest boxplot representing the cumulative risk of infection for a susceptible working utilizing the combined interventions. Boxplots display the 5$^{th}$ and 95$^{th}$ percentiles (whiskers), 25$^{th}$ and 75$^{th}$ percentiles (boxes), and median (middle line) risk of infection. Below each boxplot is the percentage infection risk reduction attributed to using the combined interventions.

**Figure 7. Fecal Event Module Spearman's Rho Correlation Coefficients**

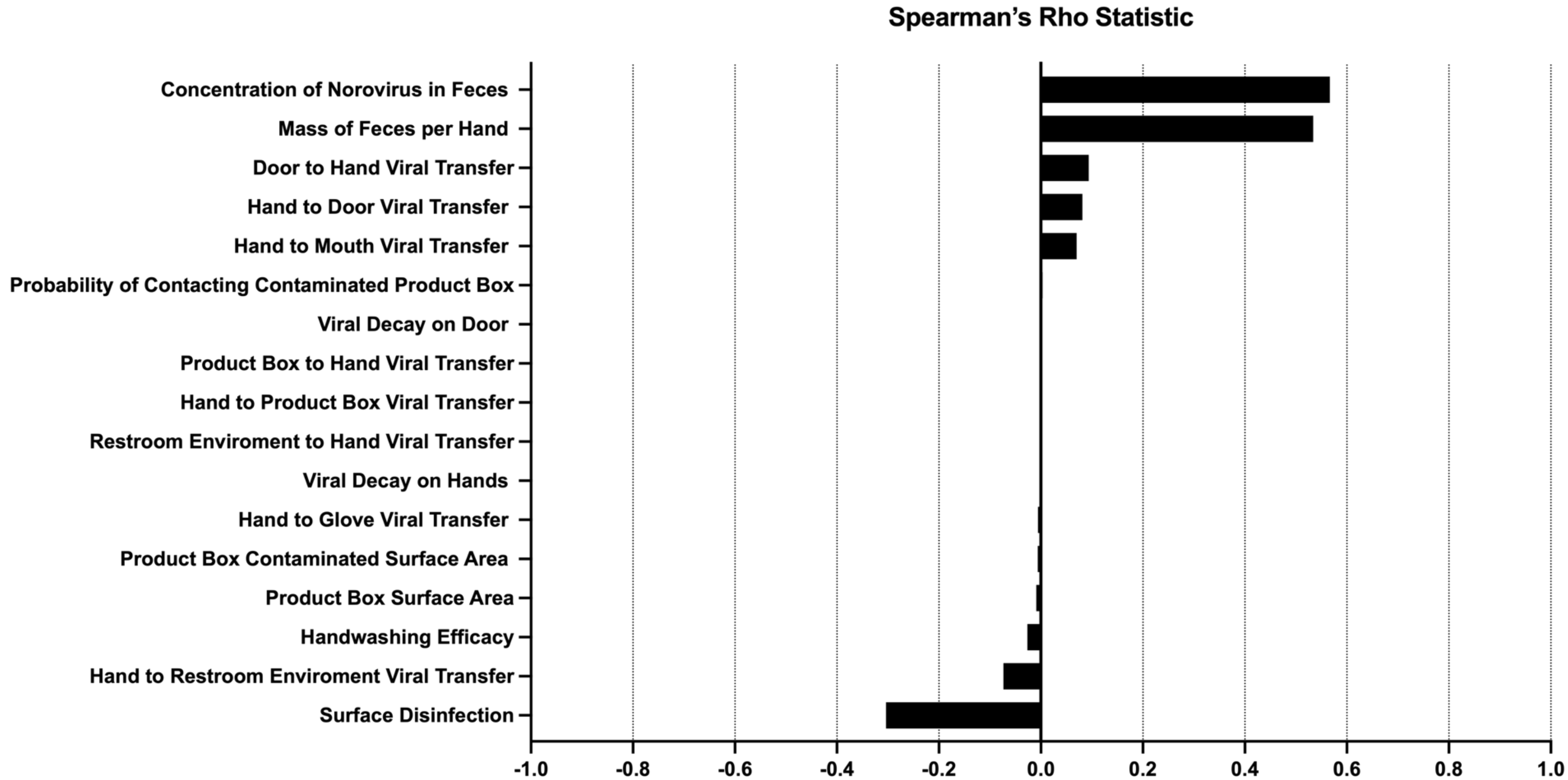


**Figure 7. Fecal event module spearman's rho correlation coefficients.** Spearman's rho correlation coefficients were calculated to assess the accumulation of variability across 10,000 model simulations. The parameters associated with an increased risk of norovirus infection are represented by the bars extending from 0 toward 1. The parameters associated with a decreased risk of norovirus infection represented by the bars extending from 0 toward -1. Parameters that were point estimates had no variability across model simulations and thus the variability attributed to these parameters could not be evaluated.

**Figure 8. Vomit Event Module Spearman's Rho Correlation Coefficients**

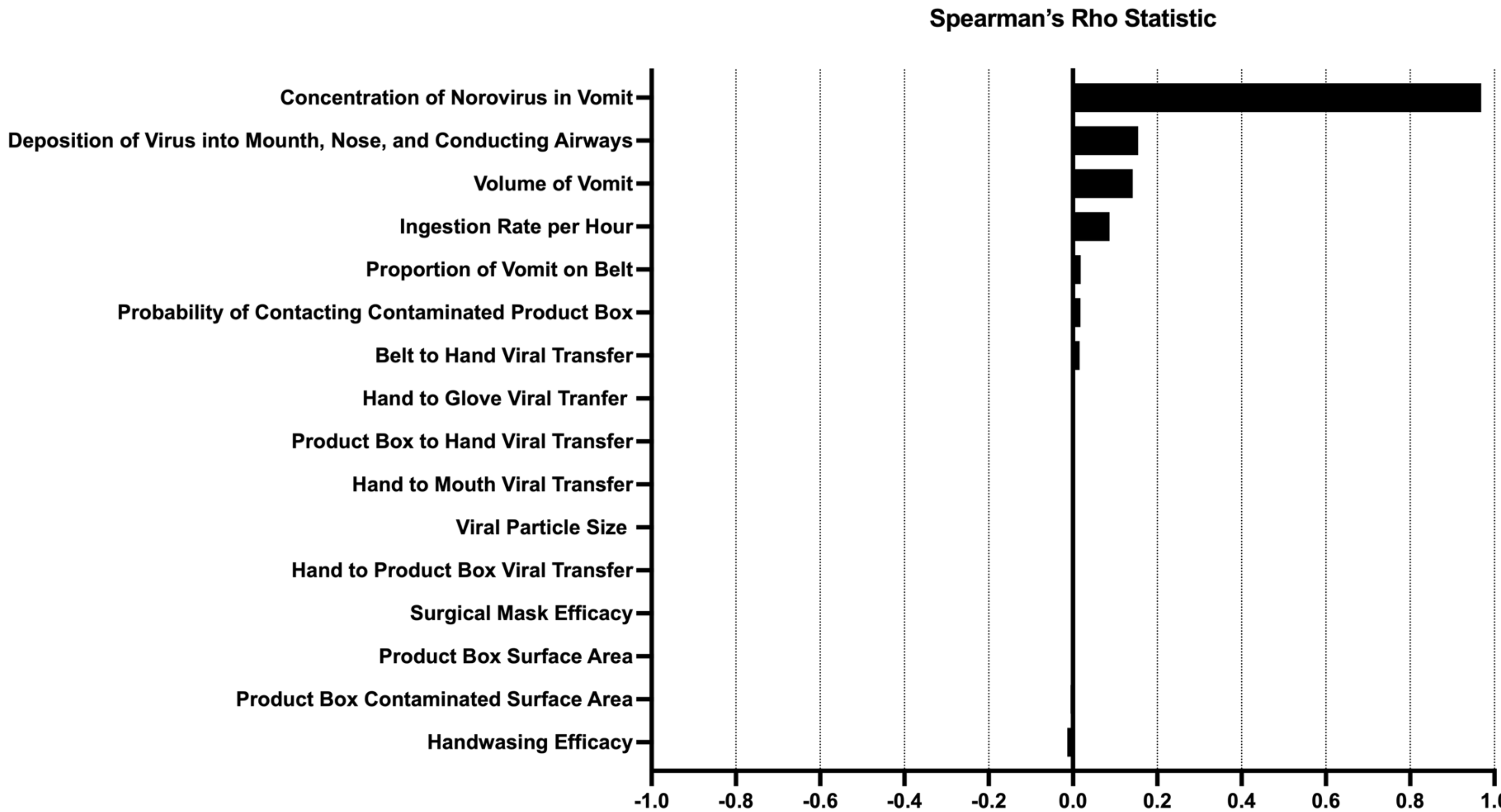


**Figure 8. Vomit event module spearman's rho correlation coefficients.** Spearman's rho correlation coefficients were calculated to assess the accumulation of variability across 10,000 model simulations. The parameters associated with an increased risk of norovirus infection are represented by the bars extending from 0 toward 1. The parameters associated with a decreased risk of norovirus infection represented by the bars extending from 0 toward -1. Parameters that were point estimates had no variability across model simulations and thus the variability attributed to these parameters could not be evaluated.