Original Contribution

The Population-Level Impacts of Excluding Norovirus-Infected Food Workers From the Workplace: A Mathematical Modeling Study

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Norovirus is the leading cause of acute gastroenteritis and foodborne disease in the United States. The Food and Drug Administration recommends that food workers infected with norovirus be excluded from the workplace while symptomatic and for 48 hours after their symptoms subside. Compliance with this recommendation is not ideal, and the population-level impacts of changes in food-worker compliance have yet to be quantified. We aimed to assess the population impacts of varying degrees of compliance with the current recommendation through the use of a compartmental model. We modeled the number and proportion of symptomatic norovirus cases averted annually in the US population (using data from 1983–2014) in specific age groups (children aged <5 years, children aged 5–17 years, adults aged 18–64 years, and adults aged ≥ 65 years) under various scenarios of food-worker exclusion (i.e., proportion compliant and days of postsymptomatic exclusion) in comparison with a referent scenario which assumed that 66.6% of norovirus-symptomatic food workers and 0% of postsymptomatic food workers were excluded from work. Overall, we estimated that 6.0 million cases of norovirus have already been avoided annually under the referent scenario and that 6.7 million (28%) more cases might be avoided through 100% compliance with the current recommendations. Substantial population-level benefits were predicted from improved compliance in exclusion of norovirus-infected food workers from the workplace—benefits that may be realized through policies or programs incentivizing self-exclusion.

disease transmission; food workers; mathematical models; norovirus; restaurant employees

Abbreviations: FDA, Food and Drug Administration; LHS, Latin hypercube sampling; UI, uncertainty interval.

Noroviruses are the most common cause of acute gastroenteritis and the leading cause of foodborne disease in the United States (1–3). The efficient transmission of norovirus is due in part to its low infectious dose (4–6), long duration of viral shedding (7), and environmental stability (8, 9) and to the multiple pathways by which the pathogen can reach a human host (i.e., person-to-person contact, food, fomites, environmental contamination) (10). In order to curtail downstream norovirus infection at the population level, it is critical to understand the attribution of norovirus disease to different transmission routes as potential points of intervention.

The National Outbreak Reporting System collects reports of enteric disease outbreaks transmitted through any means (11). From 2009 through 2012, 4,318 suspected or confirmed norovirus outbreaks were reported through the National Outbreak Reporting System, with 23% of those outbreaks being attributed to

foodborne transmission as the primary mode of transmission (11). Most reports of foodborne norovirus outbreaks have implicated food contaminated during preparation or service (92%), food prepared in a restaurant setting (64%), and infected food workers (70%) as the source of contamination (11). Additionally, nearly 20% of food workers report having worked at least 1 shift in the past year while experiencing diarrhea or vomiting (12). Fear of losing their jobs or leaving coworkers short-staffed significantly influences food workers' decisions to work while ill (12).

On the basis of restaurant studies and outbreak surveillance data (12–14), the Centers for Disease Control and Prevention stresses 3 recommendations from the Food and Drug Administration (FDA) Food Code to reduce norovirus contamination of ready-to-eat foods by food workers, namely 1) supervision by a certified kitchen manager, 2) proper practice of hand hygiene by all employees, and 3) exclusion of all ill food workers

from the workplace for at least 48 hours after symptoms subside (11, 15). While full compliance with these recommendations would undoubtedly have a positive public health impact, quantifying the potential changes in the burden of norovirus disease in the United States would allow policy-makers to compare different interventions targeting norovirus disease.

We sought to quantify potential changes in the annual burden of norovirus disease in the United States resulting specifically from exclusion of infected food workers from the workplace. As described above, food workers represent the most frequent source of foodborne norovirus outbreaks (11), and there exist sufficient data on the behavior of infected food workers for the purpose of transmission modeling (12). Compartmental models are useful for predicting population-level effects of interventions that are impractical and/or costly to test or measure in a nationally representative sample (16). In this study, we aimed to estimate the population-level effects of excluding varying proportions of 1) symptomatic food workers and 2) postsymptomatic food workers from the workplace for varying durations of time in their postsymptomatic state using a deterministic, compartmental model.

METHODS

Model design

States of infection, disease, and immunity. The Web Appendix and Web Figure 1 (available at <https://academic.oup.com/aje>) contain full details of the model; here we describe the key features. Two deterministic, population-based compartmental models were used in this study (Figure 1). The models tracked 5 states, or compartments, of norovirus infection, disease, and immunity: susceptible to disease (S), exposed (E), symptomatically infected (I), asymptomatically infected (A), and immune (R). The R compartment population represents protection against disease, but persons in this class may still become asymptomatically infected. Births occur at the same rate as deaths (Table 1). Susceptible individuals become infected (at a rate function of $\lambda_{\text{tot},i}$) and then transition to the symptomatic, postsymptomatic, and recovered compartments at rates that are reciprocals of the time spent in each previous compartment (i.e., rates of ν , ϕ , and ρ , respectively) (Table 2). The recovered population can either become asymptomatically infected (at a rate function of $\lambda_{\text{tot},i}$) or experience natural waning of immunity whereby they become susceptible to disease again (i.e., at a rate of θ) (Table 3). Our model was informed by findings from peer-reviewed publications and data from government databases ranging from 1983 to 2014.

Age and employment structure. The models further distinguished the population by age group (children aged <5 years, children aged 5–17 years, adults aged 18–64 years, and adults aged ≥ 65 years) and by food-worker employment status (i.e., consumer or food worker (F)). A proportion (τ) of children aged 5–17 years progress to the working adult age group (18–64 years) as food workers and remain food workers until they are lost to turnover (Γ), death, or retirement into the ≥ 65 -year age group. We restricted the food-worker population to the 18- to 64-year age group for simplicity and maintained it at approximately 8.2 million, as estimated by the Bureau of Labor Statistics (17).

We assumed that the force of infection experienced by consumers across all age groups and food workers resulted from exposure to fellow consumers as well as food workers through contaminated food (i.e., $\lambda_{\text{tot},i}(t)$ in the Web Appendix). Contact rates among consumers were adapted from the European POLYMOD Study (18) as used by Steele et al. (19) (Web Table 1). Within each age group, we took the weighted average of numbers of away-from-home meals consumed each year, collected from the 2011–2012 National Health and Nutrition Examination Survey (20), as a proxy for exposure to food handled by food workers. Food workers do not have higher contact rates within the food-worker class, but they do have higher rates of contact with the general population. Both force-of-infection terms (i.e., representing consumers and food workers) assumed that pre- and postsymptomatic individuals were 5% as infectious as symptomatic individuals (21).

Exclusion of infected food workers. We created additional compartments to model the exclusion of infected food workers (designated “food-worker exclusion” (FE)) from the workplace (i.e., I_{FE} and A_{FE}) for a variable period of time when postsymptomatic (i.e., A_{F1} and A_{F2}). The duration of time that nonexcluded food workers spend in A_{F1} is equal to the duration for which postsymptomatic food workers are excluded (i.e., time spent in A_{FE}). The duration nonexcluded food workers spend in compartments A_{F1} and A_{F2} is equal to the duration for which consumers are postsymptomatic (i.e., time spent in A_i). Excluding food workers from the workplace directly reduces the number of occupants in compartments I_{F} and A_{F} , thereby reducing the force of infection experienced by consumers due to contact with food workers. h_1 is the proportion of symptomatic food workers who are excluded from work, h_2 is the proportion of food workers who continue to be excluded from work when postsymptomatic, and h_3 is the proportion of food workers who are excluded from work after working while symptomatic. A scenario in which $h_2 < h_3$ and $h_3 > 0$ might reflect a situation where infected food workers continue to work while symptomatic but are subsequently excluded after a symptomatic episode at the workplace (e.g., a public vomiting event) and remain excluded from work afterwards. The model was constructed, calibrated, and simulated using R 3.3.1 (R Foundation for Statistical Computing, Vienna, Austria).

Model parameters

Tables 2 and 3 contain the parameter values, ranges, and distributions for natural history of disease, transmission, and seasonality used in our model. We used Latin hypercube sampling (LHS) to generate 1,100 random samples of parameter sets. With each fixed LHS parameter set, we refitted the model using maximum likelihood, allowing the transmission probabilities and seasonality parameters to vary for a model without food-worker compartments (Table 3) (Figure 1A). We fitted the model to monthly counts of norovirus hospitalizations by age group (22), using age-specific hospitalization probabilities calculated on the basis of age-specific incidence rates from Grytdal et al. (23) and population sizes according to the Centers for Disease Control and Prevention’s 2014 national population projections (24). We calculated negative log likelihoods assuming that the hospitalizations for each age group were Poisson-distributed with mean values equal to the model-predicted

Figure 1. States of norovirus infection, disease, and immunity among consumers and food workers (F) in a study of the population-level impacts of excluding norovirus-infected food workers from the workplace, United States, 1983–2014. A) In the consumer population, newborns enter the susceptible compartment (S) and become exposed (E) at the total force of infection ($\lambda_{tot,i}(t)$). The total force of infection is due to contact with consumers and food workers. Consumers become symptomatic (I), postsymptomatic (A), and recovered (R) at rates (i.e., μ , ϕ , and ρ , respectively) that are the inverse of the amount of time spent in each compartment. The recovered population can either become asymptomatically infected at the total force of infection or become susceptible through waning of natural immunity (θ). B) The food-worker population progresses through states of infection and immunity in the same fashion as the consumer population. Food workers may experience exclusion from the workplace (designated “food-worker exclusion” (FE)) when symptomatic (I_{FE}) and/or when postsymptomatic (A_{FE}). Excluded postsymptomatic food workers may return to work before they stop shedding virus. The duration of postsymptomatic infection for food workers ($1/\rho_1 + 1/\rho_2$) equals the duration of postsymptomatic infection for consumers ($1/\rho_1$), with both ranging from 1 day to 20 days. C) Food workers are restricted to the age group 18–64 years ($i = 3$). A proportion of children aged 5–17 years ($i = 2$) progress to the working adult age group (18–64 years) ($i = 3$) as food workers, regardless of infection, disease, or immunity state, and remain food workers until they are lost to turnover (Γ), death, or retirement into the ≥ 65 -year age group ($i = 4$).

incidence multiplied by the probability of hospitalization. Using the median age-specific transmission probabilities, we calibrated the transmission probability from infectious food workers (p) and the attribution scaling parameter (κ) for a model incorporating food workers (Figure 1), which is explained in the next section. Then, using the 1,100 LHS parameter sets, we ran the model that incorporated food workers under the referent scenario. We discarded 44 simulations where excluding symptomatic food workers led to increases in annual incidence and 4

simulations where the solver failed to integrate; this left 1,052 parameter sets for estimation of uncertainty intervals.

Model calibration

The referent scenario was defined as excluding 66.6% of symptomatic food workers and zero postsymptomatic food workers from the workplace. This percentage of symptomatic food workers was based on the 20% of food workers who

Table 1. Input Values and Sources of Demographic Parameters Used in a Study of the Population-Level Impacts of Excluding Norovirus-Infected Food Workers From the Workplace, United States, 2013–2014

Parameter and Age Group	Variable	Value	Source
Mortality rate, no. of deaths/year			
Children aged <5 years	D_1	3.72×10^{-6}	CDC, 2015 (24)
Children aged 5–17 years	D_2	4.85×10^{-7}	CDC, 2015 (24)
Adults aged 18–64 years	D_3	9.19×10^{-6}	CDC, 2015 (24)
Adults aged ≥ 65 years	D_4	1.14×10^{-4}	CDC, 2015 (24)
No. of food workers in US population	N_F	8,209,000	BLS, 2013 (17)
Food worker turnover rate, %/year	Γ	5.1	BLS, 2013 (17)
No. of persons in US population			
Children aged <5 years	N_1	19,906,993	CDC, 2015 (24)
Children aged 5–17 years	N_2	53,683,736	CDC, 2015 (24)
Adults aged 18–64 years	N_3	198,902,067	CDC, 2015 (24)
Adults aged ≥ 65 years	N_4	46,255,221	CDC, 2015 (24)

Abbreviations: BLS, Bureau of Labor Statistics; CDC, Centers for Disease Control and Prevention.

Table 2. Parameters for the Natural History of Norovirus Disease Used in a Study of the Population-Level Impacts of Excluding Norovirus-Infected Food Workers From the Workplace, United States, 1983–2012

Parameter	Variable	Input Value	Range	Distribution	Source
Duration of incubation period, hours	ψ	32.8	30.9–34.6	Uniform	Devasia, 2015 (31)
Duration of symptomatic infectiousness, hours	ϕ	48	38.9–50.7	Uniform	Devasia, 2015 (31)
Duration of postsymptomatic infectiousness, days	ρ	10	1–20	Uniform	Atmar, 2008 (7)
Duration of postsymptomatic infectiousness of food workers excluded from the workplace, days	ρ_1	2	0.2–4	Uniform	Modeled
Duration of postsymptomatic infectiousness of food workers after returning to work, days	ρ_2	8	0.8–16	Uniform	Modeled
Duration of immunity, years	θ	5.1	4.0–6.7	Uniform	Simmons, 2013 (27)

reported having worked at least 1 shift in the past year while ill with diarrhea or vomiting, reported by Carpenter et al. (12), and the 0.6 episodes of acute diarrheal illness per person per year in the United States reported by Jones et al. (25)—the latter of which we assumed was the same for the US food-worker population. Thus, the quotient 0.2/0.6 was defined as the proportion of food workers who worked while ill. The complement of this fraction (i.e., 2/3) was used as the referent proportion of ill food workers who were excluded from the workplace (h_1). Although exclusion of postsymptomatic food workers for 2 days after symptoms resolve is also recommended (11, 15), data on compliance with this recommendation were unavailable and thus this value was kept at zero in the referent scenario.

The parameter for the probability of norovirus transmission from infectious food workers through contaminated food (p) could not be estimated from empirical data. Thus, the model was calibrated by adjusting p and an attribution scaling parameter, κ , such that 1) the referent scenario would yield a national incidence of 23.3 million symptomatic norovirus cases to match age-group-specific incidence rates from Grytdal et al. (23) and 2) national incidence would be reduced by 15.7% (derivation shown in Web Appendix) when direct foodborne transmission was removed from the population (i.e., $\lambda_i(t)$ set constant, $\lambda_{i, fw}(t) = 0$). We assumed that the attributes of reported 2009–2012 norovirus outbreaks described by Hall et al. (11) were also representative of endemic norovirus cases that occur in the United States.

Model scenarios

We calculated the median values and 90% uncertainty intervals of annual norovirus incidence for complete compliance and complete lack of compliance with FDA Food Code recommendations for symptomatic and postsymptomatic food workers. The 5 scenarios simulated were: 1) no exclusion of infected food workers from the workplace (i.e., $h_1 = h_2 = h_3 = 0$); 2) the referent scenario of two-thirds of food workers being excluded only while symptomatic (i.e., $h_1 = 0.6\bar{6}$ and $h_2 = h_3 = 0$); 3) the referent scenario of two-thirds of food workers being excluded while symptomatic and for 2 days while postsymptomatic (i.e., $h_1 = 0.6\bar{6}$, $h_2 = h_3 = 1$); 4) all infected food workers being excluded only while symptomatic (i.e., $h_1 = 1$ and $h_2 = h_3 = 0$); and 5) full compliance with FDA Food Code recommendations

(i.e., $h_1 = h_2 = 1$, $h_3 = 0$, per the model structure) (Table 4). Using the 1,052 LHS parameter sets, we calculated the median value and 5th and 95th percentiles of annual incidence and annual incidence averted from scenario 2, the referent scenario. For annual incidence averted, we determined the median value and 90% uncertainty interval of the difference between incidence in counterfactual scenarios for a given LHS parameter set.

Next, using input values listed in Tables 2 and 3 alone, we simulated the number and proportion of symptomatic norovirus cases averted per year relative to the referent scenario by ranging the proportion of symptomatic food workers excluded (i.e., h_1 range = $[0, 1]$) and the proportion of postsymptomatic food workers excluded, the latter irrespective of previous symptomatic exclusion (i.e., h_2 range = h_3 range = $[0, 1]$). The number and proportion of symptomatic norovirus cases averted per year were calculated using a 10-year average to account for endemic patterns that span more than a year. The proportions of postsymptomatic exclusion were set equal (i.e., $h_2 = h_3$) for all scenarios, with the exceptions of 0% and 100% symptomatic food-worker exclusion from the workplace (i.e., $h_1 = 0$ and $h_1 = 1$, respectively). For all scenarios in which we varied the proportion of food workers excluded, we assumed that the exclusion of postsymptomatic food workers lasted 2 days (i.e., $\rho_1 = 2$), per FDA Food Code recommendations. The proportions of symptomatic food workers excluded (i.e., $h_1 = [0, 1]$) and of postsymptomatic food workers excluded (i.e., $h_2 = h_3 = [0, 1]$) were discretized at 0.1, yielding 121 sets of parameter values for model simulations.

Lastly, using only input values from Tables 2 and 3, we predicted the number of symptomatic norovirus cases averted when excluding 100% of postsymptomatic food workers for a positive, whole number of days, regardless of previous symptomatic exclusion (i.e., $h_2 = h_3 = 1.0$). For any given number of days of postsymptomatic exclusion, we still assumed that 66.6% of symptomatic food workers did not work (i.e., $h_1 = 0.6\bar{6}$).

RESULTS

Model fitting

The calibrated value for the transmission probability from infectious food workers, p , was 0.3264, and for the attribution

Table 3. Parameters for Norovirus Transmission in a Study of the Population-Level Impacts of Excluding Norovirus-Infected Food Workers From the Workplace, United States and 9 European Countries^a, 1983–2012

Parameter and Age Group	Variable	Input Value	Range ^b	Source
Relative incubation and postsymptomatic infectiousness	ε	0.05	0.045–0.055	Simmons, 2013 (27)
Probability of transmission from infectious consumer				
Children aged <5 years	q_1	0.11	0.08–0.17	Fitted
Children aged 5–17 years	q_2	0.01	0.01–0.02	Fitted
Adults aged 18–64 years	q_3	0.05	0.04–0.09	Fitted
Adults aged ≥ 65 years	q_4	0.03	0.02–0.05	Fitted
Seasonal amplitude	β_1	0.04	0.01–0.08	Fitted
Seasonal offset, day	ω	2.17	2.03–2.29	Fitted
Rate of contact made by persons in age group i , per day				
Children aged <5 years	b_1	8.12		Steele, 2016 (19)
Children aged 5–17 years	b_2	15.52		Steele, 2016 (19)
Adults aged 18–64 years	b_3	13.94		Steele, 2016 (19)
Adults aged ≥ 65 years	b_4	8.53		Steele, 2016 (19)
Rate of contact age group i makes with food workers, daily average				
Children aged <5 years	$\bar{b}_{F1}$	0.27		CDC, 2011 (20)
Children aged 5–17 years	$\bar{b}_{F2}$	1.08		CDC, 2011 (20)
Adults aged 18–64 years	$\bar{b}_{F3}$	0.57		CDC, 2011 (20)
Adults aged ≥ 65 years	$\bar{b}_{F4}$	0.26		CDC, 2011 (20)
Probability of transmission from infectious food worker	ρ	0.3264		Calibrated ^c
Attribution scaling parameter	κ	0.7529		Calibrated ^c

Abbreviations: CDC, Centers for Disease Control and Prevention; F, food worker.

^a Belgium, Finland, Germany, Great Britain, Italy, Luxembourg, the Netherlands, Poland, and Sweden.

^b The relative incubation and postsymptomatic infectiousness scaling parameter was uniformly distributed when estimating the fitted parameters.

^c Using the median values of refitted transmission probabilities and seasonality parameters, the following 2 conditions were met: The referent scenario would yield a national incidence of 23.3 million symptomatic norovirus cases to match age-group-specific incidence rates from Grytdal et al. (23) and national incidence would be reduced by 15.7% when direct foodborne transmission was removed from the population (i.e., $\lambda_{i,F}(t) = 0$).

scaling parameter, κ , it was 0.7529. Using these parameter values, our model predicted 24.3 million symptomatic norovirus cases per year (90% uncertainty interval (UI): 17.5, 32.2) under the referent scenario, which appropriately includes the target value of 23.3 million symptomatic norovirus cases per year.

Model simulations

Complete compliance and complete lack of compliance. Compared with no food-worker exclusion, our model predicts that the referent scenario of only excluding two-thirds of food workers from the workplace while they are symptomatic already averts 6.0 million (90% UI: –7.8, 20.8) symptomatic norovirus cases annually (Table 4). When excluding all symptomatic food workers, our model predicted that 5.4 million (90% UI: 2.6, 15.9) additional symptomatic norovirus cases (22.8%, 90% UI: 10.6, 53.5) would be averted annually. Furthermore, it predicted that if all infected food workers were excluded while symptomatic and

continued to be excluded for 2 days while postsymptomatic (i.e., 100% compliance with current recommendations), 6.7 million (90% UI: 3.0, 16.7) symptomatic norovirus cases (27.9%, 90% UI: 13.5, 54.9) would be averted annually.

Varying only the proportion of symptomatic workers excluded. The number (Figure 2) and proportion (Figure 3) of referent symptomatic norovirus cases averted annually are shown through various proportions of symptomatic food-worker exclusion. The smallest change in the number of symptomatic norovirus cases averted in the US population was experienced by children under age 5 years. The maximum number of symptomatic cases averted among young children was 0.65 million (90% UI: 0.28, 1.8), or a 24.2% reduction (90% UI: 11.5, 51.4), at 100% symptomatic food-worker exclusion. The largest change in number and the smallest change in proportion of symptomatic cases averted were experienced by adults aged 18–64 years. The maximum number of symptomatic cases averted among 18- to 64-year-olds was 3.3 million (90% UI: 1.2, 9.6),

Table 4. Median Values and 90% Uncertainty Intervals for Annual Norovirus Incidence and Number of Incident Norovirus Cases Averted Under Various Scenarios as Compared With a Referent Scenario, United States, 1983–2014^a

Scenario ^b	Proportion of Symptomatic Food Workers Excluded From the Workplace (h_1)	Proportion of Postsymptomatic Food Workers Excluded From the Workplace (h_2 and h_3)	No. of Symptomatic Norovirus Cases, millions/year		No. of Symptomatic Norovirus Cases Averted, millions/year		% of Symptomatic Norovirus Cases Averted	
			Median	UI	Median	UI	Median	UI
No exclusion of infected food workers from the workplace	0	0	30.4	15.3, 40.4	–6.0	–20.8, 7.8	–24.2	–119.8, 28.6
Referent scenario of two-thirds of food workers being excluded only while symptomatic	2/3	0	24.3	17.5, 32.2	— ^c		— ^c	
Referent scenario of two-thirds of food workers being excluded while symptomatic and for 2 days while postsymptomatic	2/3	1	23.2	16.1, 30.9	0.9	0.1, 2.0	3.5	0.5, 6.9
Exclusion of all infected food workers only while symptomatic	1	0	18.5	11.2, 25.5	5.4	2.6, 15.9	22.8	10.6, 53.5
Exclusion of all infected food workers while symptomatic and for 2 days while postsymptomatic	1	1 ^d	17.2	10.5, 23.6	6.7	3.0, 16.7	27.9	13.5, 54.9

Abbreviation: UI, uncertainty interval.

^a Model parameters were based on findings from peer-reviewed publications and data from government databases ranging from 1983 to 2014.

^b The 5 scenarios simulated were: 1) no exclusion of infected food workers from the workplace (i.e., $h_1 = h_2 = h_3 = 0$); 2) the referent scenario of two-thirds of food workers being excluded only while symptomatic (i.e., $h_1 = 0.6\bar{6}$ and $h_2 = h_3 = 0$); 3) the referent scenario of two-thirds of food workers being excluded while symptomatic and for 2 days while postsymptomatic (i.e., $h_1 = 0.6\bar{6}$, $h_2 = h_3 = 1$); 4) all infected food workers being excluded only while symptomatic (i.e., $h_1 = 1$ and $h_2 = h_3 = 0$); and 5) full compliance with Food and Drug Administration Food Code (15) recommendations (i.e., $h_1 = h_2 = 1$, $h_3 = 0$, per the model structure).

^c Referent.

^d $h_3 = 0$, per the model structure.

or a 23.9% reduction (90% UI: 9.2, 52.5), at 100% symptomatic food-worker exclusion. The largest proportion of symptomatic cases averted was among children aged 5–17 years, with a 46% reduction (90% UI: 28.6, 71.8), or 1.4 million cases (90% UI: 0.88, 2.3) at 100% symptomatic food-worker exclusion. For the number of symptomatic cases averted by each age group in the referent scenario alone, see Web Tables 1–3.

Varying only the proportion of postsymptomatic workers excluded. The smallest number and proportion of symptomatic cases averted were experienced by children under the age of 5 years, reaching 0.083 million cases averted (90% UI: 0.009, 0.180), or a 3.1% reduction (90% UI: 0.4, 5.9), at 100% postsymptomatic food-worker exclusion, under the referent assumption of 66.6% symptomatic food-worker exclusion. The largest number of symptomatic cases averted was experienced by adults aged 18–64 years, reaching 0.40 million cases (90% UI: 0.04, 0.95), which corresponds to a 2.8% reduction (90% UI: 0.3, 6.0) at 100% postsymptomatic food-worker exclusion, under the referent assumption of 66.6% of symptomatic food workers being excluded. The largest proportion of symptomatic cases averted was experienced by children aged 5–17 years,

reaching a 6.1% reduction (90% UI: 1.4, 10.0), which corresponds to 0.20 million cases (90% UI: 0.03, 0.42) at 100% postsymptomatic food-worker exclusion, under the referent assumption of 66.6% symptomatic food-worker exclusion.

Varying the duration of 100% exclusion of postsymptomatic workers. The number of symptomatic cases averted ranged from 0.3 million cases at 1 day of postsymptomatic exclusion to 3.8 million cases at 10 days of postsymptomatic exclusion (absolute range of 3.5 million cases) (Figure 4).

DISCUSSION

In this study, we predicted the relative impacts of symptomatic and postsymptomatic exclusion of infected food workers from the workplace on the incidence of norovirus gastroenteritis in the United States. For any given age group, the number of symptomatic cases averted (Figure 2) and the proportion of symptomatic cases averted (Figure 3) were both more sensitive to changes in the proportion of symptomatic food-worker exclusion than to changes in the proportion of postsymptomatic

Figure 2. Numbers of incident norovirus cases averted annually by excluding infected food workers from the workplace, in comparison with the referent scenario, United States, 1983–2014. Model parameters were based on findings from peer-reviewed publications and data from government databases ranging from 1983 to 2014. A) Children aged <5 years; B) children aged 5–17 years; C) adults aged 18–64 years; D) adults aged ≥65 years. The red arrowhead above the x-axis of each graph points to the referent scenario. These outputs result from varying the proportions (range, 0–1) of the food-worker population excluded from the workplace for the entirety of the symptomatic period and for 2 days out of 10 possible days while postsymptomatic. In the majority of scenarios, the proportions of postsymptomatic exclusion are the same in value regardless of symptomatic exclusion (i.e., $h_2 = h_3$). When 0% of symptomatic food workers are excluded from the workplace (i.e., $h_1 = 0$), it is impossible to model continued exclusion of postsymptomatic food workers (i.e., $h_2 = 0$), per the model construct. When 100% of symptomatic food workers are excluded from the workplace (i.e., $h_1 = 1$), it is impossible to model exclusion of postsymptomatic food workers who worked while symptomatic (i.e., $h_3 = 0$), per the model construct. For every age group, the number of symptomatic cases averted was more sensitive to changes in the proportion of symptomatic food workers excluded than to changes in the proportion of postsymptomatic food workers excluded.

Figure 3. Proportion of incident norovirus cases averted annually by excluding infected food workers from the workplace, in comparison with the referent scenario, United States, 1983–2014. Model parameters were based on findings from peer-reviewed publications and data from government databases ranging from 1983 to 2014. A) Children aged <5 years; B) children aged 5–17 years; C) adults aged 18–64 years; D) adults aged ≥65 years. The red arrowhead above the x-axis of each graph points to the referent scenario. These outputs result from varying the proportions (range, 0–1) of the food-worker population excluded from the workplace for the entirety of the symptomatic period and for 2 days out of 10 possible days while postsymptomatic. In the majority of scenarios, the proportions of postsymptomatic food workers excluded are the same in value regardless of symptomatic exclusion (i.e., $h_2 = h_3$). When 0% of symptomatic food workers are excluded from work (i.e., $h_1 = 0$), it is impossible to model continued exclusion of postsymptomatic food workers (i.e., $h_2 = 0$), per the model construct. When 100% of symptomatic food workers are excluded from the workplace (i.e., $h_1 = 1$), it is impossible to model the exclusion of postsymptomatic food workers who worked while symptomatic (i.e., $h_3 = 0$), per the model construct. For every age group, the proportion of symptomatic cases averted was more sensitive to changes in the proportion of symptomatic food workers excluded than to changes in the proportion of postsymptomatic food workers excluded.

Figure 4. Numbers of symptomatic norovirus cases averted annually for a given number of days of excluding 100% of postsymptomatic food workers from the workplace (i.e., $h_2 = h_3 = 1.0$), in comparison with the referent scenario, United States, 1983–2014. Model parameters were based on findings from peer-reviewed publications and data from government databases ranging from 1983 to 2014. Here, it is still assumed that 66.6% of symptomatic food workers are excluded (i.e., $h_1 = 0.66$). Population totals are denoted for each day excluded, and the counts are further broken down by age group (≥ 65 years, 18–64 years, 5–17 years, and < 5 years).

food-worker exclusion. Nevertheless, there were differences in the relative impacts on specific age groups. The greatest number of symptomatic cases averted was among adults aged 18–64 years because of the absolute size of this age group. The greatest proportion of symptomatic cases averted was among children aged 5–17 years, because a greater proportion of their meals, in comparison with that of other age groups, is prepared by food handlers away from home. Lastly, we found that full compliance with FDA Food Code recommendations for exclusion of ill food workers could avert about 28% (90% UI: 13.5, 54.9) of the currently observed norovirus incidence in the United States.

A key strength of our modeling approach was the capacity to estimate the effects of exclusion of infected food workers from the workplace. Such effects on consumers are indirect and therefore require a transmission model for simulation. We considered a range of scenarios (i.e., a range of parameter values). Furthermore, our model was parameterized on the basis of a number of inputs sourced from peer-reviewed and official sources. Our model incorporated multiple transmission routes and a separate occupational class of food workers, allowing us to investigate the epidemiology of norovirus as a result of food-worker interactions with the wider population.

We made a number of simplifying assumptions in line with the level of detail from the literature for parameterization. First, we assumed cross-protection in our single-strain model (26), because currently data are insufficient for parameterizing a multistrain model. While this would affect the natural history of

disease parameters within our model, we would expect annual incidence averted to follow the same trend within and between age groups when varying the proportion of infected food workers who were compliant and the number of days of postsymptomatic food-worker exclusion. The 15.7% of norovirus disease attributable to food workers was based on reported outbreak data, which may have been biased considering the state-to-state variation in reporting rates (11). Additionally, our model used meals eaten away from home as an indicator of food-worker exposure, which may not directly reflect the number of meals served by food workers. Finally, we assumed that postsymptomatic infectiousness remained constant at 5% of the infectiousness of symptomatic food workers for the entire duration of the postsymptomatic state. This change in infectiousness to a smaller, constant value reflects evidence of postsymptomatic shedders contributing less to transmission (21) and explains why the model predicted a greater impact of symptomatic exclusion on norovirus burden compared with postsymptomatic exclusion. However, this model feature does not reflect the gradual reduction in norovirus shedding observed in human challenge studies (7), nor does it reflect the potential changes in human behavior (i.e., contact rates) over the course of the symptomatic and postsymptomatic periods.

The specific assignment of 5% infectiousness in our model was adopted from the model input parameters used by Simmons et al. (27). The greater transmission potential of symptomatic individuals compared with postsymptomatic individuals can be explained by the transmission potential of the symptoms themselves, namely acute-onset diarrhea and vomiting (21, 28). Transmission is also possible while food workers are postsymptomatic. In fact, an analysis of stool samples collected from food workers who were present during norovirus outbreaks and sporadic cases in food-catering settings in Japan revealed that postsymptomatic food workers possessed mean viral loads similar to those of symptomatic food workers (29). Still, the relative roles of symptomatic and postsymptomatic food workers in transmission remain unclear, despite both having contributed to outbreaks.

Findings from studies on the restaurant industry and food workers' behavior offer ideas for future adaptations of our model. For instance, it has been shown that the presence of a certified kitchen manager in restaurants is associated with fewer norovirus-associated outbreaks and with the absence of bare-hand contact with ready-to-eat foods, identified as a contributing factor (13). Additionally, food workers have been observed to attempt to wash their hands before only 32% of work activities that require hand-washing, and to appropriately wash their hands before only 27% of such work activities (14). The possible extensions of our model will be determined by the degree of detail of empirical data collected in the future for these situations. Once available, such data will allow investigators to explore the interplay of multiple norovirus interventions on the population level. Additionally, assessment of the potential population impacts of candidate norovirus vaccines used among food workers (30) could likewise be incorporated into this model.

The large number and proportion of symptomatic norovirus cases averted with increased exclusion of symptomatic food workers and the additional reduction in symptomatic norovirus cases afforded through postsymptomatic exclusion support current recommendations by the Centers for Disease Control

and Prevention and by the FDA. Our findings show that with limited resources, priority should be given to enforcing exclusion of symptomatic food workers from the workplace over exclusion of postsymptomatic workers. In this study, we considered the impact of behavior change which might be realized through policy and enforcement, including educational campaigns, incentives (e.g., sick pay), loss of pay for working while ill, or other interventions that would encourage infected food workers to practice self-exclusion more. Our model construction allows for 1) modeling other interventions targeting food workers and 2) comparing population-level effects of other norovirus interventions such as vaccines. Studies that quantify in more detail the social networks of excluded infected food workers, nonexcluded infected food workers, and consumers are needed in order to better inform future models concerning the potential economic value and public health benefits of specific interventions targeting food workers.

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