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Hand hygiene and surface cleaning should be paired for prevention of fomite transmission

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Hand hygiene and surface cleaning should be paired for prevention of fomite transmission

Abstract

Touching contaminated surfaces might lead to the spread of pathogens, i.e. the fomite transmission route. Although hand and surface hygiene practises are potentially important non-pharmaceutical interventions for the fomite route, the two interventions have been mostly studied separately in the literature. In this study, we develop a new conceptual model based on the law of mass action, analyse the temporal diffusion of contaminated surfaces and hands, and verify the model with simulations in an assumed norovirus outbreak in a buffet restaurant. A quantitative hygiene criterion is developed for the required frequency of surface disinfection and hand hygiene to control the fomite transmission in indoor environments. To eliminate surface contaminations, the product of pathogen-removal rates (including hygiene and natural death) on hands and surfaces must be no smaller than that of the human hand and surface contact frequency (i.e., the net removal product must be non-negative). When the net removal product is negative, the number of contaminated surfaces and hands would show logistic growth trend and finally approach equilibrium. Our approach sheds light into how to optimize the combined use of hand hygiene and environmental decontamination for the best effectiveness under different settings.

(192 words)

Key words: Hand hygiene; Surface cleaning; Infection control; Fomite transmission; Surface/hand contamination; Hygiene criterion.

Practical Implications

To the best of our knowledge, this study is the first to propose a quantitative hygiene criterion for the required frequency of surface cleaning and hand hygiene to control the fomite transmission in various built environments. Our study also reveals that a combination of hand hygiene and surface cleaning is more effective than any single intervention and that these two interventions cannot be studied alone. Our findings suggest that hand hygiene alone is insufficient as a control measure for the fomite transmission of pathogens, and must be paired with surface cleaning.

1. Introduction

People spend most of their time in indoor environments[1] and inevitably touch many surrounding environmental surfaces every day. A susceptible person can potentially become infected by touching a pathogen-contaminated surface, also called fomites, and then touching susceptible sites on his or her body[2,3]. This transmission mode is called the fomite route. In recent years, evidence has grown to support the important role of this route in the transmission of pathogens[4,5], especially those with strong survival ability on surfaces, such as norovirus[6] and methicillin-resistant *Staphylococcus aureus* (MRSA)[7].

The propagation of surface contamination by the fomite route seems to be straightforward in a surface contamination network[8], as shown in Figure 1. A surface contaminated by a particular source might be touched by several people, and these individuals then touch and contaminate other surfaces with their contaminated hands as they move around. As the surface touching goes on, the surface contaminations diffuse, as long as the source of contamination is strong enough[9]. Several studies[8,10] have found that frequent hand-surface contact can lead to rapid diffusion of surface contamination, which follows a logistic growth trend. However, the quantitative relationship between surface touching and hand/surface hygiene remains unclear, which makes it difficult to predict the temporal characteristics of fomite transmission and develop appropriate control measures.

<Fig. 1>

Hand and surface hygiene practises are potentially important nonpharmaceutical interventions for the fomite route[11]. Theoretically, these methods can reduce the spread of pathogens by breaking the fomite transmission chain[12]. Authorities such as World Health Organization (WHO) and Centers for Disease Control and Prevention (CDC) often recommend these methods for control of various pathogens[13-15]. However, the evidence for the effectiveness of these two interventions is insufficient[16,17]. Several controlled trials found no statistically significant reductions in pathogen spread after hand or surface hygiene methods were implemented[18,19]. Therefore, the key questions are raised and require to be addressed: Can surface and hand hygiene prevent the fomite transmission of pathogens? If so, how frequently should we clean hands and surfaces?

In this study, we used the classical law of mass action to develop an ordinary differential equations (ODEs) model to explore the influence of hand–surface touch frequency and hand/surface hygiene rates on the temporal diffusion of contaminated surfaces. Moreover, we performed multi-agent simulations to verify the ODEs model in an assumed case of norovirus transmission in a buffet restaurant. The findings of this study inform recommendations for proper hygiene rates for hands and surfaces to control the fomite transmission of pathogens, based on hand–surface touching behaviours in various enclosed environments.

2. Methods

2.1 Ordinary differential equations model

The ODEs model was developed to quantify the relationship between the growth in the number of contaminated surfaces (contaminated with live pathogens), the hand-surface touching frequencies and the pathogen-removal rates from hands and surfaces.

Our model in an enclosed environment was based on the following assumptions:

- For simplicity, we focused on dynamics of the influential surfaces in the control equations, i.e. common surfaces that can be touched by all the individuals. In this study, surfaces only referred to common surfaces, and those which are never touched or which are touched by only one person were excluded.
- The total number of surfaces, N_s, and the population size, N_p, were constant ($N_s = N_{sd}(t) + N_{sc}(t)$, $N_p = N_{pd}(t) + N_{pc}(t)$), where $N_{sd}(t)$ and $N_{sc}(t)$ were the number of dirty and clean surfaces at time t, and $N_{pd}(t)$ and $N_{pc}(t)$ were the number of individuals (people) with dirty and clean hands at time t, respectively. A dirty surface or hand denotes a surface contaminated with live pathogens. We assumed that the two hands of any individual are always either both clean or both contaminated, so that the percentage of people with dirty hands equals the percentage of contaminated hands.
- Populations touch portions of surfaces homogeneously, that is, individuals touch each surface with the same probability during a time unit.
- Contact with a pathogen-contaminated surface or hand was assumed to always lead to the contamination of the contacting hand/surface, regardless of whether the contamination concentration on the surface/hand was low or high.

- Pathogen transfer from hands to susceptible sites on the body was not modelled, such as the loss of pathogens during eye-rubbing, nose-picking and mouth-touching.
- Pathogen cleaning was performed uniformly and thoroughly on surfaces and on hands. For example, a surface clean rate of 0.2/min means that one surface was disinfected every 5 minutes and that the disinfection efficacy was 100%.

The model parameters are defined in Table 1.

<Table 1>

In each time unit, $c_p \times N_p$ surface-hand contact events occur. The creation of a new dirty hand occurred only when a clean hand touched a dirty surface. During hand-surface contact, the possibility of the hand initially being clean was $\frac{N_{pc}(t)}{N_p}$, and the possibility of the surface initially being dirty was $\frac{N_{sd}(t)}{N_s}$. Assuming that populations touch fomites homogeneously, the application of the law of mass action led to the total times of clean hands touching dirty surfaces in a time unit being calculated by: $c_p N_{pc}(t) \frac{N_{sd}(t)}{N_s} (= c_p \times N_p \times \frac{N_{sd}(t)}{N_s} \times \frac{N_{pc}(t)}{N_p})$.

The temporal change in the number of people with dirty hands ($\frac{dN_{pd}(t)}{dt}$) equalled the total new number of people who got their hands dirty by touching dirty surfaces ($c_p N_{pc}(t) \frac{N_{sd}(t)}{N_s}$) minus the number of people who cleaned their dirty hands ($r_p N_{pd}(t)$). Thus, the governing equation for the number of people with dirty hands became:

$$\frac{dN_{pd}(t)}{dt} = c_p N_{pc}(t) \frac{N_{sd}(t)}{N_s} - r_p N_{pd}(t)$$

Similarly, the temporal change in the number of dirty surfaces ($\frac{dN_{sd}(t)}{dt}$) equalled the new number of surfaces that became dirty after being touched by dirty hands ($c_s N_{sc}(t) \frac{N_{pd}(t)}{N_p}$) minus the number of surfaces that were cleaned ($r_s N_{sd}(t)$). Thus, the governing equation for the number of dirty surfaces became:

$$\frac{dN_{sd}(t)}{dt} = c_s N_{sc}(t) \frac{N_{pd}(t)}{N_p} - r_s N_{sd}(t)$$

For normalisation, the fractions of the contaminated surfaces and individuals with dirty hands $\frac{N_{pd}(t)}{N_p}$ and $\frac{N_{sd}(t)}{N_s}$ were denoted as $n_{pd}(t)$ and $n_{sd}(t)$, with the value ranging from 0 to 1.
Thus, the two governing equations became

$$\begin{cases} \frac{dn_{pd}(t)}{dt} = c_p n_{sd}(t)(1 - n_{pd}(t)) - r_p n_{pd}(t) \\ \frac{dn_{sd}(t)}{dt} = c_s n_{pd}(t)(1 - n_{sd}(t)) - r_s n_{sd}(t) \end{cases} \quad (1)$$

No analytical solutions exist for the system of Equation 1, so we performed simple analysis and applied an explicit Runge–Kutta-Fehlberg method (4,5)[20] to acquire numerical solutions to determine the conditions for growth or decline in the number of dirty surfaces or hands. This conceptual model of surface/hand contamination and hygiene dynamics (Equation 1) is an application of the classical law of mass action, which has also been used to describe chemical reactions[21], mathematical ecology such as predator–prey equations[22] and infectious disease modelling such as the SEIR (Susceptible–Exposed–Infectious–Recovered) model[23].

2.2 Assumed case of norovirus transmission in a buffet restaurant

To verify the ODEs model, we performed multi-agent simulations[9,24] in an assumed case of norovirus transmission in a buffet restaurant and compared the simulation results with the numerical solutions of the model. As shown in Figure 2, we assumed the restaurant provided 100 buffet dishes, each with a utensil (spoon/tongs) for guests to serve their own food. Forty guests have a 2-h dinner there, one of whom is an infector carrying a large number of noroviruses on his or her hands. Thus, the crowdedness α equals 0.4 (=$\frac{40}{100}$) in this case. The guests were assumed to randomly pick up food from one dish every 4 minutes and had no body contact with each other. Thus, in this case, the frequency for a hand to contact surfaces c_p was 0.25/min, and correspondingly the frequency for a surface to contact hands c_s (=$\frac{c_p N_p}{N_s}$) was 0.1/min according to the definition in Table 1.

<Fig. 2>

The guests and the restaurant had no idea of the existence of the norovirus infector, so no targeted control measures were implemented. The guests occasionally cleaned their hands, and the restaurant routinely cleaned some serving utensils. The inactivation rate of norovirus on hands (skin surfaces) b_p is 0.04/min[25], and that on serving utensils (non-porous surfaces) b_s is 0.002/min[26].

We considered two situations, and the parameter values were summarized in Table 2. In the first, the compliance with hand and surface hygiene was poor. We assumed that no guests cleaned their hands (hand-hygiene frequency h_p= 0) and that the restaurant staff cleaned a serving utensil every 55 minutes (surface-hygiene frequency h_s=0.018/min). Thus, the pathogen-removal rate from hands r_p(=b_p+h_p) was 0.04/min, and that from surfaces r_s(=b_s+h_s) was 0.02/min, which made the product $r_p r_s$ (0.008/min^2) less than $c_p c_s$ (0.025/min^2). Initially, only the infector was assumed to carry noroviruses on his or her hands, and the surfaces and the other guests' hands were assumed to be clean (i.e., the initial values for the percentage of the contaminated hands and surfaces $n_{pd}(0)$ and $n_{sd}(0)$ were 1/40 and 0, respectively).

In the second situation, the compliance with hand and surface hygiene was high. We assumed guests cleaned their hands every 17 minutes (hand-hygiene frequency h_p= 0.06/min) and that the restaurant cleaned a serving utensil every 2.5 minutes (surface-hygiene frequency h_s=0.4/min). Thus, the pathogen-removal rates from hands r_p(=b_p+h_p) was 0.10/min, and that from surfaces r_s(=b_s+h_s) was 0.40/min, which made the product $r_p r_s$ (0.04/min^2) greater than $c_p c_s$(0.025/min^2). We assumed that the infector shook hands with the other guests before the dinner and used the serving utensils to try all the dishes, so all hands and surfaces were contaminated at the beginning of the dinner (i.e., the initial values $n_{pd}(0)$ and $n_{sd}(0)$ were 1 and 1, respectively).

In the multi-agent simulations, we used a discrete-time Markov chain model to simulate the influence on norovirus transmission by a series of behaviours, including guests touching public environmental surfaces (i.e., serving utensils), guests cleaning their hands and the restaurant staff cleaning public surfaces. The parameter values in the multi-agent simulations are kept the same with those in the ODEs model as listed in Table 2. In the multi-agent simulations, all the guests were taken as agents. The heterogeneity for each agent was retained, and agents shared the same behavioral rules but did not act synchronously. For example, two guests picked up food from dishes at the same frequency, but their might have different choices and their behaviors might occur at different time points. Thus, in different simulations, the sequences and the exact timings of behaviors vary. We ran 1000 simulations to calculate the temporal growth of the contaminated environmental surfaces and hands and compared the average results with the numerical solutions of the ODEs model.

Apart from the parameter values listed in Table 2, we further conducted sensitivity analyses to the primary parameters c_p, c_s, r_p and r_s in the governing equations (Equation 1) to appropriately quantify the uncertainties of the results. The hand/surface contact frequencies c_p and c_s and pathogen-removal rates on hands/surfaces r_p and r_s ranged from 0.02 to 1 with a common difference of 0.02.

2. Results

3.1 Dynamics analysis

Our developed model (Equation 1) was a non-linear dynamical system that could predict the changes of the percentage of dirty hands or surfaces over time. Figure 3 shows the phase portrait to represent the trajectories of this dynamical system in the n_{pd}-n_{sd} phase plane. The two curves that satisfied $\frac{dn_{pd}(t)}{dt} = 0$ and $\frac{dn_{sd}(t)}{dt} = 0$ (i.e., the percentage of people with dirty hands $n_{pd}(t)$ and the percentage of dirty surfaces $n_{sd}(t)$ that did not change with time *t*) could be obtained by solving Equation 1. We thus obtained:

$$n_{sd} = \frac{r_p n_{pd}}{c_p(1-n_{pd})}, n_{pd} = \frac{r_s n_{sd}}{c_s(1-n_{sd})}$$

We drew the two curves that satisfied these two equations in the n_{pd}-n_{sd} phase plane, as shown in Figure 3. In the range from 0 to 1, the two curves continuously increased. The growth rate of the curve for the equation $n_{sd} = \frac{r_p n_{pd}}{c_p(1-n_{pd})}$ increased, whilst that for the equation $n_{sd} = \frac{c_s n_{pd}}{r_s+n_{pd}}$ decreased. The slopes of the two curves were r_p/c_p and c_s/r_s at the origin ($n_{sd} = 0, n_{pd} = 0$), respectively.

<Fig. 3>

As shown in Figure 3a, when $r_p/c_p < c_s/r_s$ i.e. $r_p r_s - c_p c_s < 0$, in addition to the origin, these two curves met at the intersection (the blue point) $(\frac{c_p c_s - r_p r_s}{c_p(c_s+r_s)}, \frac{c_p c_s - r_p r_s}{c_s(c_p+r_p)})$. In the area above the black curve $n_{sd} = \frac{r_p n_{pd}}{c_p(1-n_{pd})}$ (namely $\frac{dn_{pd}(t)}{dt} = 0$), the percentage of pathogen-contaminated surfaces n_{sd} was greater than $\frac{r_p n_{pd}}{c_p(1-n_{pd})}$, so $\frac{dn_{pd}(t)}{dt}$ was greater than 0 according to Equation 1. In contrast, in the area below the black curve, $\frac{dn_{pd}(t)}{dt}$ was less than 0. Similarly, in the area above the red curve $n_{pd} = \frac{r_s n_{sd}}{c_s(1-n_{sd})}$ (namely $\frac{dn_{sd}(t)}{dt} = 0$), the percentage of pathogen-contaminated hands n_{pd} was less than $\frac{r_s n_{sd}}{c_s(1-n_{sd})}$, so $\frac{dn_{sd}(t)}{dt}$ was less than 0 according to Equation 1. In contrast, in the area below the red curve, $\frac{dn_{sd}(t)}{dt}$ was greater than 0. Taking the area above the black curve and below the red curve as an example, both $\frac{dn_{pd}(t)}{dt}$ and $\frac{dn_{sd}(t)}{dt}$ were greater than 0 in this area, which means that both $n_{pd}(t)$ and $n_{sd}(t)$ increase with time *t*. Thus, the points in this area tended towards the intersection of the two curves (the blue point), $(\frac{c_p c_s - r_p r_s}{c_p(c_s+r_s)}, \frac{c_p c_s - r_p r_s}{c_s(c_p+r_p)})$, over time. Similarly, the points in the other three areas also tended to the intersection (the blue point) over time, as represented by the directions of the arrows in Figure 3a. Therefore, the system of the ODEs model achieves a globally stable state at the intersection (the blue point).

As shown in Figure 3b. When $r_p/c_p \geq c_s/r_s$, i.e. $r_p r_s - c_p c_s \geq 0$, the two curves only met at the origin (the blue point), (0, 0). Similar to the above analyses, we found that in the area above the black curve $n_{sd} = \frac{r_p n_{pd}}{c_p(1-n_{pd})}$ (namely $\frac{dn_{pd}(t)}{dt} = 0$), the growth of the percentage of pathogen-contaminated surfaces $\frac{dn_{pd}(t)}{dt}$ was greater than 0, whilst in the area below the black curve, $\frac{dn_{pd}(t)}{dt}$ was less than 0. In the area above the red curve $n_{pd} = \frac{r_s n_{sd}}{c_s(1-n_{sd})}$ (namely $\frac{dn_{sd}(t)}{dt} = 0$), the growth of the percentage of pathogen-contaminated hands $\frac{dn_{sd}(t)}{dt}$ was less than 0, whilst in the area below the red curve, $\frac{dn_{sd}(t)}{dt}$ was greater than 0. Taking the area below the black curve and above the red curve as an example, both $\frac{dn_{pd}(t)}{dt}$ and $\frac{dn_{sd}(t)}{dt}$ were less than 0 in this area, which meant that both $n_{pd}(t)$ and $n_{sd}(t)$ decreased with time *t*. Thus, the points in this area tended towards the origin (the blue point) over time. Similarly, the points in the other two areas also tended to the origin (the blue point) over time, as represented by the directions of arrows in Figure 3b. Therefore, the system of the ODEs model achieved a globally stable state at origin.

The analyses of the dynamics system empirically suggested the difference in the products of the removal rates and the contact rates was a key parameter. We denoted this product difference the net removal product, NRP = $r_p r_s - c_p c_s$. When NRP < 0, the percentage of pathogen-contaminated hands $n_{pd}(t)$ and surfaces $n_{sd}(t)$ reached a non-zero equilibrium of $\frac{c_p c_s - r_p r_s}{c_p(c_s+r_s)}$ and $\frac{c_p c_s - r_p r_s}{c_s(c_p+r_p)}$ respectively as time *t* goes to infinity; when NRP ≥ 0, the number of pathogen-contaminated surfaces and individuals with pathogen contaminated hands finally became extinct.

3.2 Growth of the number of contaminated surfaces and hands

Figure 4 shows the predicted temporal changes of the percentage of contaminated hands and surfaces in the hypothetical buffet restaurant, by using both multi-agent simulations and numerical solutions of the ODEs model. The large scatter between individual multi-agent simulation results was caused by the randomness of human behaviours, which were considered in our simulations. The guests randomly picked up food with serving utensils, and guests and the restaurant randomly cleaned hands and surfaces, so the simulations differed. Therefore, a strategy to control the growth of the number of contaminated surfaces and hands should be developed based on average results rather than an individual one. The numerical solutions of the ODEs model can afford a rapid and good estimation of the average of 1000 simulation results, as indicated by the coefficients of determination R^2 0.99, 0.99, 1.00 and 0.94 for Figures 4a, b, c and d, respectively[27].

<Fig. 4>

As shown in Figures 4a and b, when the net removal product NRP $r_p r_s - c_p c_s < 0$, the growths in the percentages of contaminated hands $n_{pd}(t)$ and surfaces $n_{sd}(t)$ followed an *S*-shaped logistic curve in time, which increased slowly at first, then exponentially, and finally grew slowly to a maximum. In the first stage, $n_{pd}(t)$ and $n_{sd}(t)$ were small, so most contacts occurred between clean hands and clean surfaces. As the percentage of contaminated hands $n_{pd}(t)$ grew, the possibility for contaminated hands to contaminate clean surfaces during contacts increased, which accelerated the growth of the percentage of contaminated surfaces $n_{sd}(t)$. Similarly, the growth of $n_{sd}(t)$ also accelerated the growth of $n_{pd}(t)$. Therefore, the growth rates of the percentage of contaminated hands $n_{pd}(t)$ and surfaces $n_{sd}(t)$ increased in the first stage.

In the latter stage, $n_{pd}(t)$ and $n_{sd}(t)$ are large, and thus contacts mostly occurred between contaminated hands and surfaces. As the percentage of contaminated hands $n_{pd}(t)$ grew, the possibility for contaminated surfaces to contaminate clean hands during contacts decreased, which in turn slowed the change in $n_{pd}(t)$. Similarly, the growth of the percentage of contaminated surfaces $n_{sd}(t)$ also slowed. Therefore, the growth rates of the percentage of contaminated hands $n_{pd}(t)$ and surfaces $n_{sd}(t)$ decreased in the second stage. As the time *t* approaches infinity, the growth rates of $n_{pd}(t)$ and $n_{sd}(t)$ approached 0, and $n_{pd}(t)$ and $n_{sd}(t)$ reached a maximum of 0.8345 and 0.8067, which was consistent with their estimated equilibrium values from the dynamics analysis of the ODEs model in Section 3.1, as given by $\frac{c_p c_s - r_p r_s}{c_p(c_s + r_s)}$ and $\frac{c_p c_s - r_p r_s}{c_s(c_p + r_p)}$, respectively.

As shown in Figures 4c and d, when the net removal product $r_p r_s - c_p c_s \geq 0$, the reductions of the percentages of contaminated hands $n_{pd}(t)$ and surfaces $n_{sd}(t)$ followed an exponential decay curve in time. As the percentage of contaminated hands $n_{pd}(t)$ decreased, the possibility for contaminated hands to be cleaned during the hand hygiene decreased, which in turn slowed the reduction of $n_{pd}(t)$. Similarly, the reduction in the percentage of contaminated surfaces $n_{sd}(t)$ also slowed the reduction of $n_{sd}(t)$. Therefore, the reduction rates of the percentage of contaminated hands $n_{pd}(t)$ and surfaces $n_{sd}(t)$ always decreased. As the time *t* approached infinity, the reduction rates of $n_{pd}(t)$ and $n_{sd}(t)$ approached 0, and $n_{pd}(t)$ and $n_{sd}(t)$ would finally become extinct, which was consistent with the estimation from the dynamics analysis of the ODEs model in Section 3.1.

3.3 Time for contaminated hands and surfaces to reach the equilibrium state or to vanish

According to the analyses in Section 3.2, when the compliance with hand and surface hygiene was poor (the net removal product NRP, i.e. $r_p r_s - c_p c_s < 0$), the percentage of contaminated hands $n_{pd}(t)$ and surfaces $n_{sd}(t)$ approached a maximum as time *t* approached infinity. For example, in Figures 4a and b, n_{pd} and n_{sd} were close to their maximum values after 70 minutes. Because the maximum could never be reached, we estimated the time for both n_{pd} and n_{sd} to reach 99% of the maximum by numerical solutions, which was denoted as the equilibrium time $te_{0.99}$ (min).
When the compliance with hand and surface hygiene was high (the net removal product $r_p r_s - c_p c_s \geq 0$), the number of contaminated hands $n_{pd}(t)$ and surfaces $n_{sd}(t)$ vanished as time *t* approached infinity. For example, in Figures 4c and d, n_{pd} and n_{sd} were close to 0 after 70 minutes. Because this minimum could never be reached, we estimated the time for both n_{pd} and n_{sd} to reach 1% by numerical solutions, which was denoted by the vanishing time $tv_{0.01}$ (min).
To better control the fomite transmission, we could either delay the equilibrium time $te_{0.99}$, or reduce the vanishing time $tv_{0.01}$. Therefore, we investigated the result of the equilibrium time $te_{0.99}$ and the vanishing time $tv_{0.01}$ with hand/surface contact frequency c_p and c_s and pathogen-removal rates on hands/surfaces r_p and r_s ranging from 0.02 to 1, as shown in Figure 5. When $r_p r_s$ and $c_p c_s$ were very close, the equilibrium time $te_{0.99}$ and the vanishing time $tv_{0.01}$ were much greater than in the other scenarios, so we ignored these extreme scenarios and instead calculated the equilibrium time $te_{0.99}$ in 3,045,567 scenarios with $c_p c_s \geq 1.05 r_p r_s$ (as shown in Figure 5a) and calculated the vanishing time $tv_{0.01}$ in another 3,045,567 scenarios with $r_p r_s \geq 1.05 c_p c_s$ (as shown in Figure 5b).

We found that Figures 5a and b were symmetrical; that is, the average time in scenarios with $r_p = p$ and $r_s = q$ equalled that with $r_p = q$ and $r_s = p$ (where *p* and *q* are nonnegative numbers). With a constant product $r_p r_s$ (e.g., the ten curves in Figure 5a), the time $te_{0.99}$ in scenarios with equivalent r_p and r_s was no larger than that in other scenarios, which was especially evident with $r_p r_s$ less than 0.1. According to the inequality of arithmetic and geometric means, we have $r_p + r_s \geq 2\sqrt{r_p r_s}$. Thus, the greater of a pair of inequivalent r_p and r_s was greater than the equivalent r_p and r_s, which slowed the growth of $n_{pd}(t)$ or $n_{sd}(t)$ corresponding to the larger value of r_p and r_s toward the equilibrium state, according to Equation 1. For example, it took more time for $n_{pd}(t)$ to reach the equilibrium state when r_p equalled 0.9 and r_s equalled 0.1 than it did when both r_p and r_s equalled 0.3, although the products $r_p r_s$ were equivalent. This finding revealed that when the compliance with hand and surface hygiene was poor, inequivalent pathogen-removal rates on hands and surfaces usually delayed the time to reach the equilibrium state relative to the time to reach equilibrium with equivalent pathogen-removal rates.

With a constant product $r_p r_s$ (e.g., the ten curves in Figure 5b), the time $tv_{0.01}$ in scenarios with equivalent r_p and r_s is also no greater than in the other scenarios, which is especially evident with $r_p r_s$ less than 0.1. Similarly, we have $r_p + r_s \geq 2\sqrt{r_p r_s}$, so the lesser of a pair of inequivalent r_p and r_s will be less than the equivalent r_p and r_s, which slows the reduction of $n_{pd}(t)$ or $n_{sd}(t)$ corresponding to the lesser value between r_p and r_s toward 0, according to Equation 1. For example, it took more time for $n_{sd}(t)$ to vanish when r_p equalled 0.9 and r_s equalled 0.1 than when r_p and r_s both equalled 0.3, although the products $r_p r_s$ were equivalent. This finding revealed that when the compliance to hand and surface hygiene was high, equivalent pathogen-removal rates on hands and surfaces usually shortened the time for surface contaminations to vanish than did inequivalent rates.

<Fig. 5>

From Figure 5, we found that the equilibrium time $te_{0.99}$ and the vanishing time $tv_{0.01}$ when c_p was similar to c_s and r_p was similar to r_s were very close to those when c_p equalled c_s and r_p equalled r_s. Therefore, we derived the analytical solutions of the equilibrium time $te_{0.99}$ and the vanishing time $tv_{0.01}$ when c_p equalled c_s and r_p equalled r_s and obtained the formulas for the instances when c_p was similar to c_s and r_p was similar to r_s by trial and error. The details of the derivation are provided in Supplementary Materials. We denoted the lesser value of the initial percentages $n_{pd}(0)$ and $n_{sd}(0)$ as $n_{d0,s}$ and the greater value as $n_{d0,l}$. When $c_p c_s \geq 1.05 r_p r_s$, the ratios $\frac{c_p}{c_s}$ and $\frac{r_p}{r_s}$ ranged from 0.2 to 5, and the initial percentages $n_{pd}(0)$ and $n_{sd}(0)$ were close to 0, the formula for the equilibrium time $te_{0.99}$ was:

$$te_{0.99} = [ln\frac{99}{n_{d0,s}} + ln\frac{2*(c_p c_s - r_p r_s)}{\sqrt{c_s c_p}(c_p + c_s + r_p + r_s)}](c_p + c_s + r_p + r_s)/[2(c_p c_s - r_p r_s)].$$

When $r_p r_s \geq 1.05 c_p c_s$, the ratios $\frac{c_p}{c_s}$ and $\frac{r_p}{r_s}$ ranged from 0.2 to 5, and the initial percentage $n_{pd}(0)$ and $n_{sd}(0)$ were close to 100%, the following formula for the vanishing time $tv_{0.01}$ was:

$$tv_{0.01} = [ln\, n_{d0,l} + \ln(100 - \frac{99\sqrt{c_p c_s}}{\sqrt{r_p r_s}})](c_p + c_s + r_p + r_s)/[2(r_p r_s - c_p c_s)].$$

Figures 6a shows the comparison of the equilibrium time $te_{0.99}$ calculated by the formulas and numerical solutions in 2,034,922 scenarios, and Figure 6b shows the comparison of the vanishing time $tv_{0.01}$ calculated by the two methods in another 2,034,922 scenarios. The coefficients of determination R^2 for Figures 6a and b were 0.99 and 0.96 respectively, which indicated the formulas could accurately estimate the equilibrium time $te_{0.99}$ and the vanishing time $tv_{0.01}$ in the specific conditions[27].

<Fig. 6>

4. Discussion

To the best of our knowledge, this study is the first to propose a quantitative hygiene criterion for the required frequency of surface disinfection and hand hygiene to control the fomite transmission in indoor environments. Specifically, to eliminate surface contaminations, the product of pathogen-removal rates (including hygiene and natural death) on hands and surfaces $r_p r_s$ must be no smaller than that of the human hand and surface contact frequency $c_p c_s$ (i.e., the net removal product NRP $r_p r_s - c_p c_s$ must be non-negative).

This hygiene criterion provides the minimum requirement for pathogen-removal rates as shown by both ODE modelling and multi-agent simulations. The use of this hygiene criterion could be beneficial for the management and allocation of cleaning resources in a cost-effective way[12]. In addition, the hygiene criterion reveals that when developing strategies for hand and surface hygiene, we should consider the overall hand–surface contact frequency and the primary species of pathogens in the environments. Since the net removal product NRP $r_p r_s - c_p c_s$ equals $r_p r_s - \alpha {c_p}^2$, it required higher hygiene frequencies in crowded environments with a large crowdedness α than those with a small crowdedness α[9] to eliminate the contamination. For example, the hygiene requirements in hospitals in which dozens of inpatients share the same general medical ward[28] will be higher than those in hospitals in which inpatients are widely distributed throughout several private patient wards[9]. Moreover, the hand hygiene and surface cleaning targeted at removal of pathogens with strong environmental survivability, such as noroviruses[29], should be enhanced compared to those aimed at pathogens with high inactivation rates on surfaces, such as influenza viruses[30].

The hygiene criterion (the net removal product NRP $r_p r_s - c_p c_s \geq 0$) and the analyses of the vanishing time $tv_{0.01}$ have demonstrated the closely related relationship between pathogen-removal rates on hands r_p and on surfaces r_s. Hand hygiene and surface hygiene are inherently part of the same surface contamination network[8] and combine to cause an increase or decrease of the number of contaminated hands and surfaces after some root hands or surfaces become contaminated. If we overemphasise hand hygiene and ignore surface cleaning, or the converse, the time for surface contamination to vanish will be prolonged, and even the surface contamination transmission will not vanish but go on. This might explain the unexpected findings that hand hygiene alone or surface cleaning alone failed to reduce pathogen transmission in several controlled trials[18,31-34]. Our new theory suggests that when conducting similar research, we could compare the effectiveness of hand hygiene alone, surface cleaning alone and hand hygiene plus surface cleaning to determine whether the combination of hand and surface hygiene interventions affords better prevention of pathogen transmission than a single type of hygiene intervention. Our new theory also suggests that when testing new disinfectants for hands (or surfaces), other parameters such as surface cleaning (or hand hygiene) must also be considered. This is perhaps the most important finding of this study.

This study also revealed that if little or no hygiene is performed (NRP = $r_p r_s - c_p c_s < 0$), the percentages of pathogen-contaminated hands and surfaces increased rapidly via an *S*-shaped logistic growth curve and approached the equilibrium state as the time approached infinity. The rapid transmission of contaminations between surfaces has also been suggested by simulation studies[8,24], non-microbial marker experiments[10,35], microbiologic measurements[36] and outbreak investigations[37]. The logistic growth of contaminated surfaces was first found in a simulation study of two inflight norovirus outbreaks[8] and a fluorescence-based experimental study in an air cabin mock-up[10].

Our study developed the formulas to calculate the percentages of contaminated hands and surfaces in the equilibrium state, i.e. $n_{pd} = \frac{c_p c_s - r_p r_s}{c_p(c_s + r_s)}$ and $n_{sd} = \frac{c_p c_s - r_p r_s}{c_s(c_p + r_p)}$. According to the solutions, if the pathogen-removal rates r_p and r_s were significantly less than the hand-surface contact frequency c_p and c_s, the percentages in the equilibrium state would be close to 1, which meant that most hands and surfaces may ultimately be contaminated (see Figures 4a and b). This might explain the occurrence of a 6-day flight norovirus outbreak: despite the hygiene of surfaces near the source patient on the first day, sustained transmission of norovirus continued to occur among flight attendants working on successive flight sectors on the same airplane over the next 5 days[38]. Therefore, after an outbreak, to avoid any residual exposure in the environment, surface cleaning should not be limited only to those in the vicinity of the source. Furthermore, the high prevalence of surface contaminations also suggests that the fomite route has the ability to spread across a long distance[39], which shows that this ability should not be regarded as a unique feature of the airborne route, as is commonly believed[40].

This study has three major limitations. The first lies in the assumption that contact with a pathogen-contaminated surface (or hand) will always lead to the contamination of the contact hand (or surface). In reality, when the pathogen concentration on a surface (or hand) is low enough, further contact will not lead to the transmission of pathogens[41]. In future, more studies are needed to determine the minimum pathogen concentration required on surfaces and hands to enable further pathogen transmission during hand-surface contact. The second lies in the assumption that people touch portions of the fomites homogeneously. In reality, people may touch surfaces with different probabilities[42,43], influenced by several factors such as spatial positions and occupations[44]. In future, we will account for the inhomogeneity of people's touching behaviours to improve the accuracy and validity of our model. The third lies in the fact that only number of contaminated surfaces is considered in our model, while the exact concentration or amount of contamination, and thus exposure was not considered in our evaluation of the effectiveness of the hygiene intervention.

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Supplementary materials

The details of the derivation of formulas to calculate the time for percentages of contaminated hands and surfaces to reach the equilibrium maximum and to vanish in the specific conditions are provided in Supplementary Materials.

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Figure 1 Illustration of surface contamination diffusion process for the fomite route. Initial contamination of surfaces may be induced by the deposition of expired pathogen-containing droplets from the infector or by direct touching by the contaminated hand of the infector.

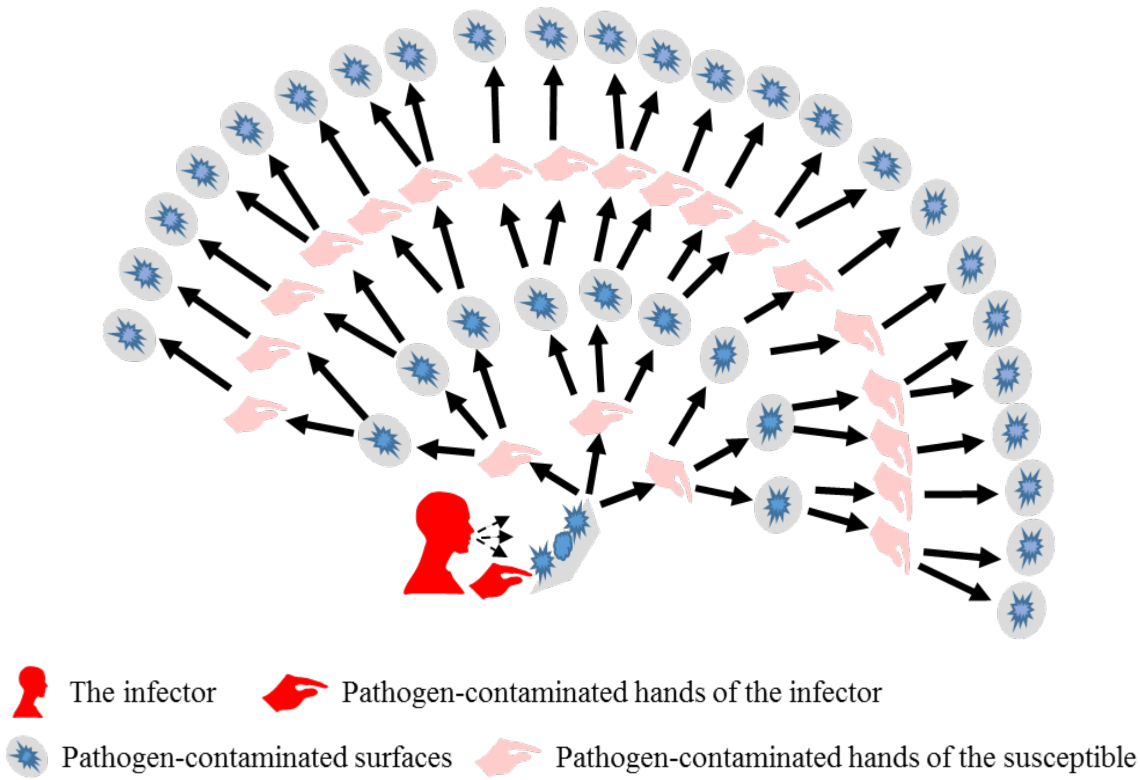


Figure 2 Assumed context of norovirus transmission in a buffet restaurant. The restaurant offers 100 buffet dishes, and 40 guests have a 2-hour dinner. The 40 guests include one norovirus infector, marked in light red.

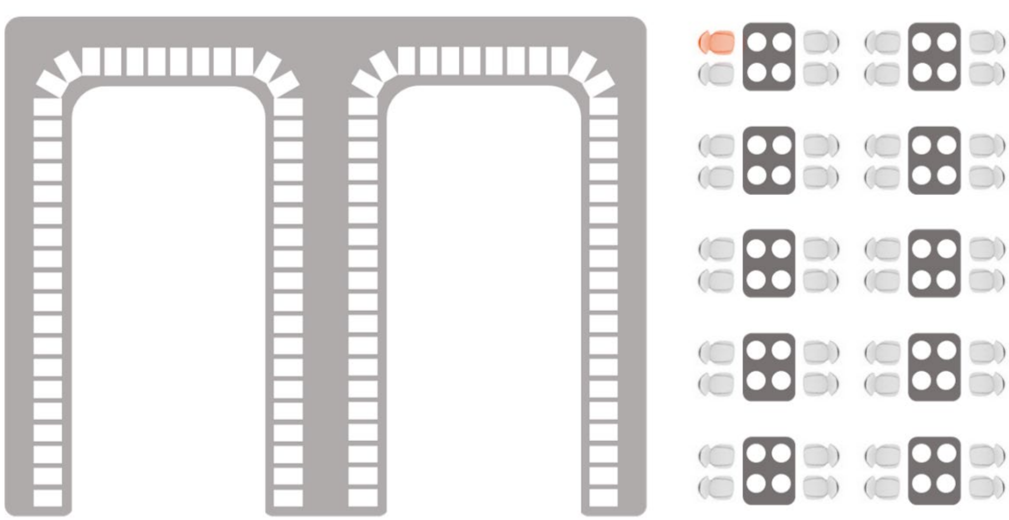
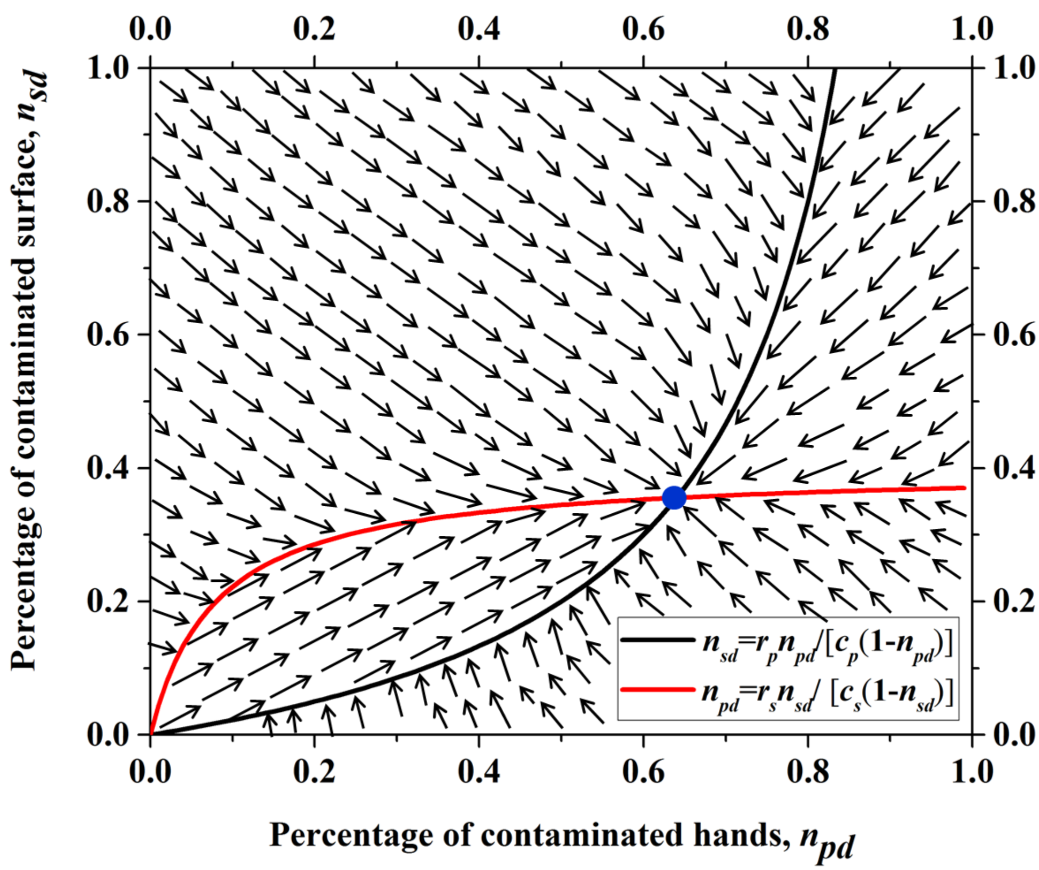
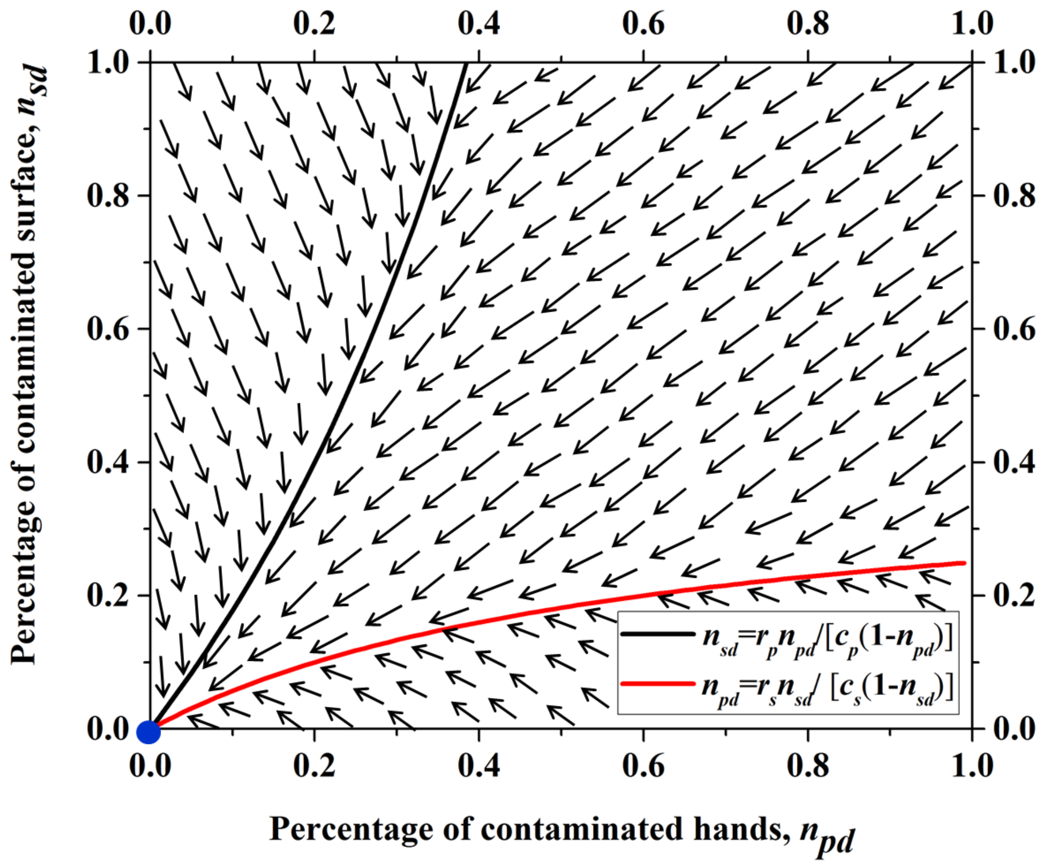


Figure 3 Phase portrait of the system of the ODEs model for various values of parameters (a) when $r_p r_s - c_p c_s < 0$; (b) when $r_p r_s - c_p c_s \geq 0$. In (a), c_p, c_s, r_p and r_s are 0.5, 0.4, 0.1 and 0.08/min, respectively; in (b), c_p, c_s, r_p and r_s are 0.5, 0.4, 0.8 and 0.6/min. The blue points in (a) and (b) indicate the globally stable states of the system in the two conditions, respectively. The directions of the arrows indicate changes in the values of n_{pd} and n_{sd} in various areas over time.



(a)



(b)

Figure 4 Temporal changes of the percentage of contaminated hands and surfaces (a) n_{pd} and (b) n_{sd} with the net removal product $r_p r_s - c_p c_s < 0$, and (c) n_{pd} and (d) n_{sd} with the net removal product $r_p r_s - c_p c_s \geq 0$ in the assumed case of norovirus transmission in a buffet restaurant from simulations and numerical solutions. In (a) and (b), the initial percentages $n_{pd}(0)$ and $n_{sd}(0)$ were 1/40 and 0, c_p, c_s, r_p and r_s were 0.25/min, 0.10/min, 0.04/min and 0.02/min, and the maxima for n_{pd} and n_{sd} are 0.8345 and 0.8067, respectively. In (c) and (d), the initial percentages $n_{pd}(0)$ and $n_{sd}(0)$ were 1 and 1, c_p, c_s, r_p and r_s were 0.25/min, 0.10/min, 0.10/min and 0.40/min, respectively. The coefficients of determination R^2 for (a), (b), (c) and (d) were 0.99, 0.99, 1.00 and 0.94, respectively.

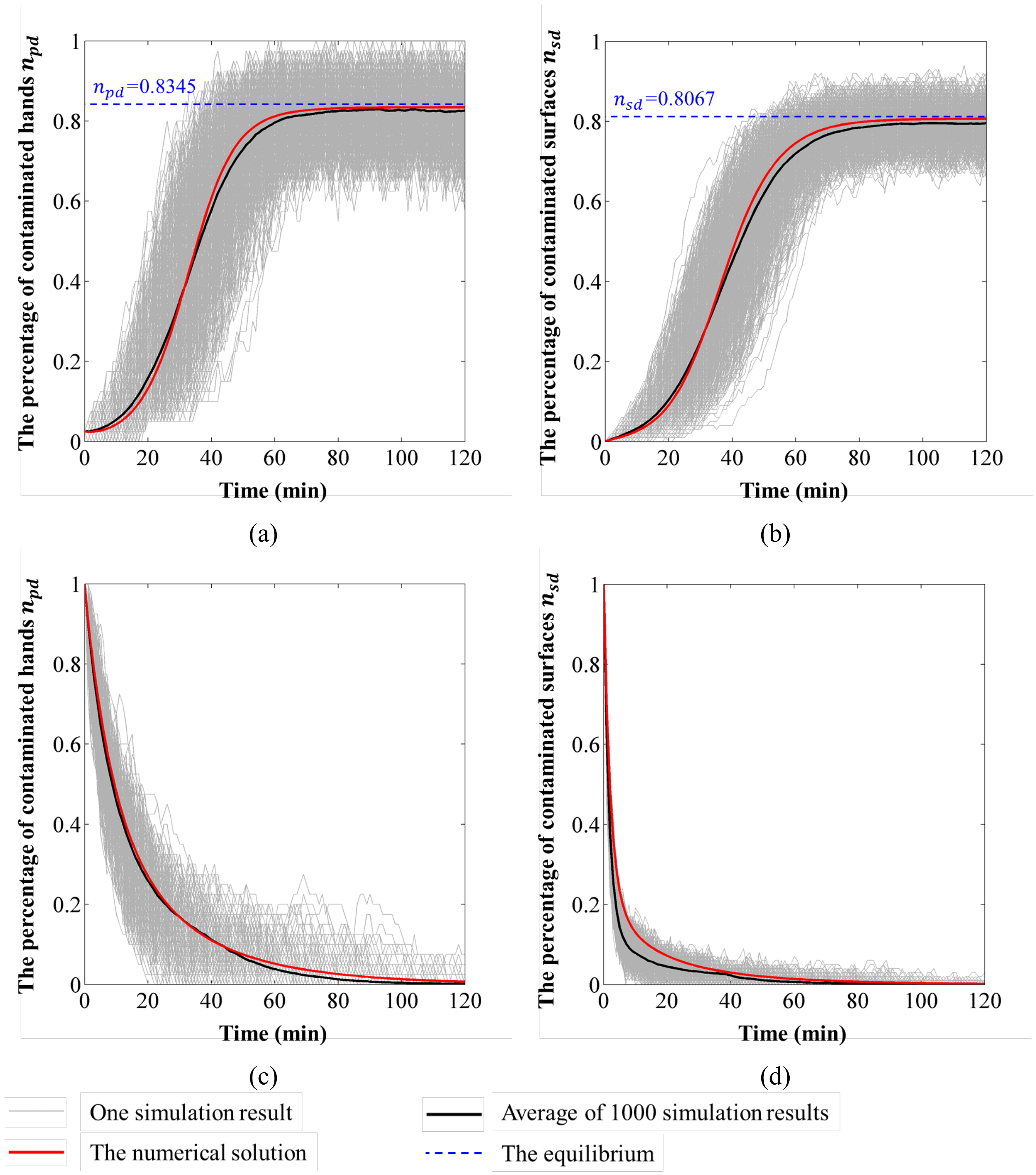
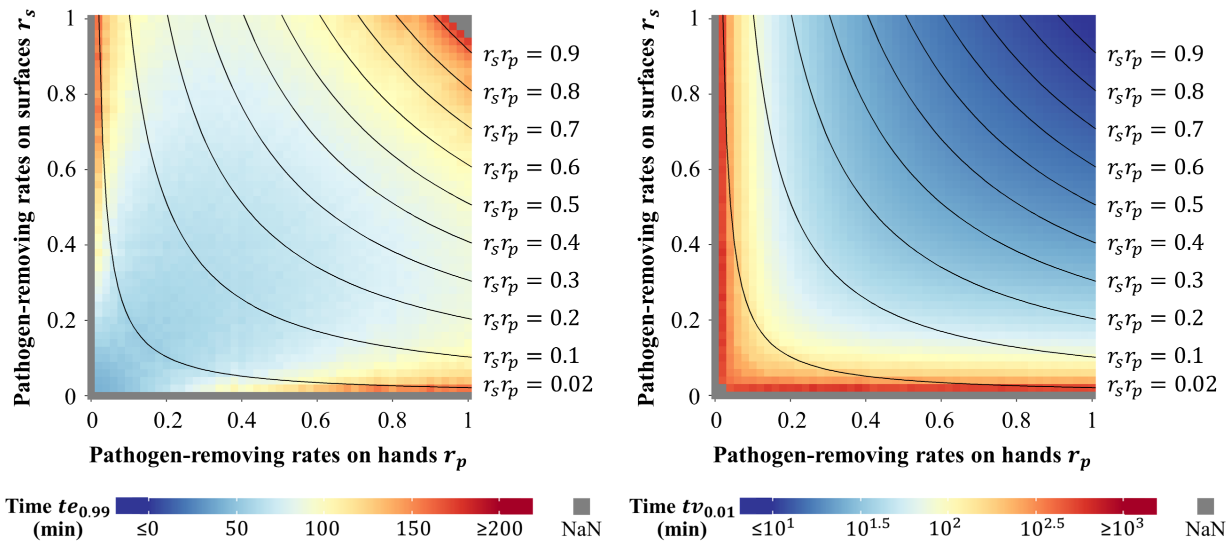


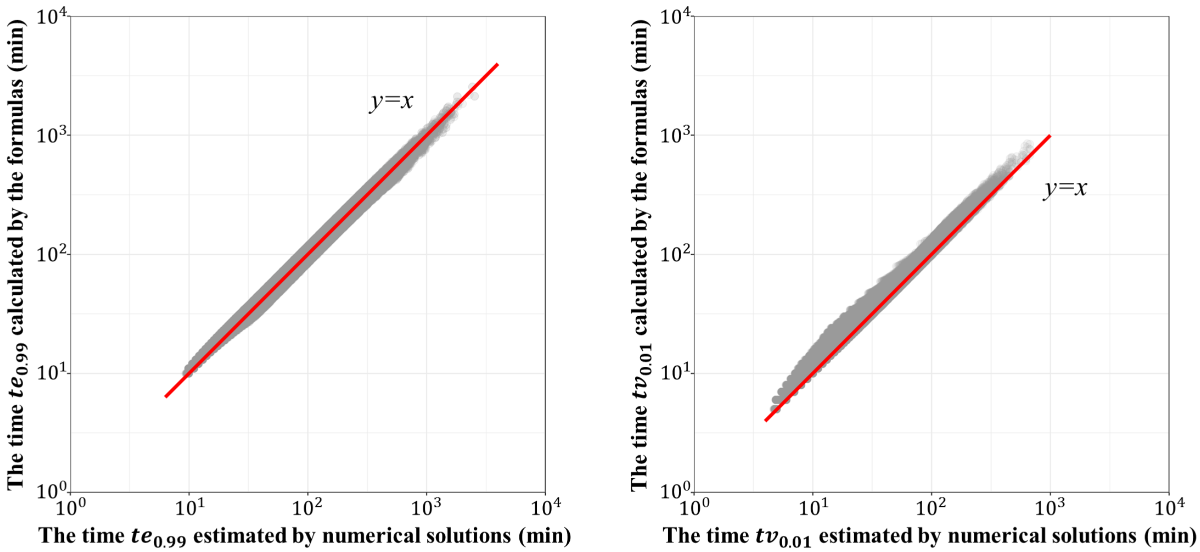
Figure 5 Heat maps showing how the values of pathogen-removal rates on hands/surfaces r_p, r_s influence (a) the equilibrium time $te_{0.99}$ when $c_p c_s \geq 1.05 r_p r_s$ and c_p, c_s, r_p, r_s $\in$\{0.02, 0.04, …, 1.00\}; (b) the vanishing time $tv_{0.01}$ when $r_p r_s \geq 1.05 c_p c_s$ and c_p, c_s, r_p, r_s $\in$\{0.02, 0.04, …, 1.00\}. The initial fractions $n_{pd}(0)$ and $n_{sd}(0)$ were 1% in (a) and 100% in (b). As shown in the legend, the colour of a square represented the average time in scenarios with a certain set of r_p and r_s, as c_p and c_s varied. In (a), the scenarios in which r_p or r_s equalled 0 and that the product $r_p r_s$

was greater than 0.95 did not exist; in (b), the scenarios in which r_p or r_s equalled 0 and that the product $r_p r_s$ was less than 0.0004 did not exist. These non-existing scenarios are shown in grey. The ten curves corresponded to the ten scenarios in which the product $r_p r_s$ was constant, at the value indicated.



(a) (b)

Figure 6 Comparison of the results calculated with the formulas and estimated by numerical solutions (a) for the equilibrium time $te_{0.99}$ when $c_p c_s \geq 1.05 r_p r_s$; (b) for the vanishing time $tv_{0.01}$ when $r_p r_s \geq 1.05 c_p c_s$. In (a), c_p, c_s, r_p, r_s ∈{0.02, 0.04, …, 1.00}, $\frac{c_p}{c_s}, \frac{r_p}{r_s} \in [0.2, 5]$, and the initial fractions $n_{pd}(0)$ and $n_{sd}(0)$ were 1%; in (b), c_p, c_s, r_p, r_s ∈{0.02, 0.04, …, 1.00}, $\frac{c_p}{c_s}, \frac{r_p}{r_s} \in$ [0.2, 5], and the initial fraction $n_{pd}(0)$ and $n_{sd}(0)$ are 100%. The red line $y = x$, denotes the points at which no differences exist between the time calculated by the formulas and that estimated by numerical solutions. The coefficients of determination R^2 for (a) and (b) are 0.99 and 0.96, respectively.



(a) (b)

Table 1 Important parameters in the ODEs model.

Parameters	Description
c_p	Mean hand contact frequency, defined as the total number of surface-hand contacts per unit time divided by the number of people N_p.
c_s	Mean surface contact frequency, defined as the total number of surface-hand contacts per unit time divided by the number of surfaces N_s, i.e. $c_s N_s = c_p N_p$.
α	Crowdedness, defined as the ratio of the number of people N_p and the number of surfaces N_s, i.e. $\alpha = N_p/N_s = c_s/c_p$.
r_p	Pathogen-removal rates on individual hands, including by hand hygiene h_p and the natural death of pathogens on hands b_p, i.e. $r_p = h_p + b_p$.
r_s	Pathogen-removal rates on surfaces, including by surface cleaning h_s and the natural death of pathogens on surfaces h_s, i.e. $r_s = h_s + b_s$.

TABLE 2 Parameter values in the poor-hygiene and good-hygiene situations of the assumed case.

Parameters	**Poor-hygiene situation**	**Good-hygiene situation**
The number of individuals N_p	100	100
The number of surfaces N_s	40	40
The crowdedness α	0.4	0.4
Mean hand contact frequency c_p	0.25/min	0.25/min
Mean surface contact frequency c_s	0.1/min	0.1/min
The inactivation rate of norovirus on hands b_p	0.04/min	0.04/min
The inactivation rate of norovirus on surfaces b_s	0.002/min	0.002/min
Hand-hygiene frequency h_p	0	0.06/min
Surface-hygiene frequency h_s	0.018/min	0.4/min
Pathogen-removal rates on individual hands r_p	0.04/min	0.10/min
Pathogen-removal rates on surfaces r_s	0.02/min	0.40/min
The initial values for the percentage of the contaminated hands $n_{pd}(0)$	1/40	1
The initial values for the percentage of the contaminated surfaces $n_{sd}(0)$	0	1