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Characterizing dynamic transmission of contaminants on a surface touch network

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ABSTRACT

Our understanding of the fomite transmission route of diseases remains at an empirical level. There are no data on how surface contamination is propagated by human touching. We designed a novel and effective benchtop experiment to investigate the dynamic transmission of contaminants on multiple environmental surfaces due to touching. The benchtop experiment setting design was based on an inflight norovirus outbreak. Hundreds of representative environmental surfaces in the plane were scaled down, and fluorescent particles were used as surrogate indicators of virus-laden aerosols. The fluorescent particles were initially carried by six index "patients" and then transmitted to other surfaces through the touching behavior of one hundred and twenty-four "passengers." The distributions of fluorescent particles were photographed by cameras when exposed to UV light and the acquired photos were processed using fluorescence imaging techniques to quantify fluorescent particles on each surface. The temporal diffusion of contaminated surfaces was found to follow an *S*-shaped logistic curve. The aisle seats were found to be more contaminated, which was consistent with the reported higher attack rates in passengers seating along the aisle in the outbreak. This study confirmed the findings of the logistic growth from the multi-agent simulations, and provided a possible mechanism for the role played by environmental surfaces in the fomite route of diseases.

1. Introduction

People in modern society live, study, and work in indoor environments [1] most of the time, and inevitably touch numerous surfaces in their daily activities. The surfaces around us may not be microscopically clean, and many studies have detected viruses [2–4], bacteria [5,6], and fungi [7,8] on indoor surfaces. Some of these microorganisms are pathogenic and could survive for several days or even months [9,10], which provides possibilities for the fomite transmission of related gastrointestinal, skin, and respiratory infections [11]. Although once thought to be negligible [12,13], the role of the fomite route in disease transmission is supported by many studies [14], including observational epidemiologic studies [15,16], intervention studies [17,18], and outbreak reports [19,20].

Our understanding of the fomite route remains at an empirical level [18,21]. Although it appears straightforward, information on the propagation process of contaminations on multiple surfaces is very limited. In indoor environments, the multiple surfaces are not independent but are linked by hands through human touching behavior, thus constructing a surface touch network [22]. Once one or some surfaces are contaminated in this network, contaminants can be passed by hands to a large number of surfaces, as long as the source of contamination is strong enough. Due to the diversity of network structures, the diffusion of contaminants on the surface network presents different temporal and spatial characteristics.

There have not been any studies of the surface network except Lei et al. [22]. Several mathematical models have been used to study how contaminants diffuse across multiple surfaces, such as the discrete-time Markov chain model [23], the differential equation model [24], and the multi-agent model [25], but few experiments have been conducted because the sequential detection of surface contaminations is a challenging task. Common techniques used to quantify microorganisms on multiple surfaces such as hybridization-based [26] and polymerase-chain-reaction-based techniques [27] have their limitations. Small samples wiped from an environmental surface do not reflect the overall degree of contaminations [28], while large samples or the original surfaces only allow one-time measurements. In this study, fluorescent particles were used as surrogate indicators. These emit visible light

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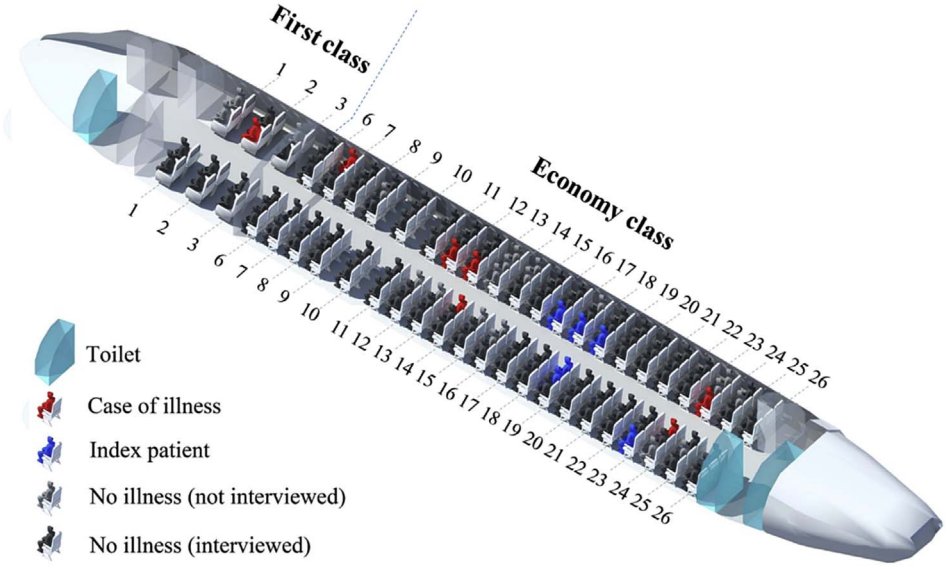

Fig. 1. The seating plan on the plane with the norovirus outbreak in October 2008, adapted from Kirking et al. [20]. The index patients, infected passengers, and uninfected passengers (including both those interviewed and not interviewed) are marked with different colored symbols. Row numbers are marked, with Rows 1–3 representing first class and Rows 6–26 representing economy class. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

when exposed to UV light, and the luminance of emitted light monotonically increases with the quantities of particles [29], which enables multiple quantification measurements. Fluorescent particles have been used in several studies to measure the transfer of contaminants [30,31] but usually on a small scale, such as on human hands, which cannot provide enough information about how contaminants are transferred on a surface touch network.

Here, we describe a novel and effective benchtop experiment. Chips of different materials present in an environment of interest are placed on a large table in a temperature- and humidity-controlled room. Participants are instructed to touch the chips in a specific sequence, defined based on the observation data in the environment of interest. To demonstrate our new method, an inflight norovirus outbreak [20] was chosen as the scenario for the experiment, as shown in Fig. 1. Six passengers from the same tour group were considered as possible index patients. Since the first-class rows were screened off from the others, we only considered the transmission between passengers in economy class. During the 2.5-h flight, 6 of 71 non-tour group passengers in economy class who were interviewed after the flight [20] developed the same kind of gastric illness. Statistics showed that sitting in an aisle seat was associated with the development of illness (P = .022, 1-sided Chi-square test). The modeling results in Lei et al. [22] also showed that the contamination conditions on surfaces of aisle seats were worse than others, and correspondingly passengers sitting there had higher infection risks.

In the benchtop experiment setting, hundreds of representative environmental surfaces in the economy class of the plane were scaled down and fluorescent particles on each surface were quantified using fluorescence imaging techniques. The quantification results were compared with the multi-agent modeling results in Lei et al. [22] and the attack rate distribution in Kirking et al. [20]. The results reported present the dynamic and rapid transmission of contaminants on multiple environmental surfaces, and confirm the findings from multi-agent simulations.

2. Methods

2.1. Materials

With low pigment residues and significant intensity changes to exposures [31], fluorescent particles from GloGerm™ were selected in the experiments. The diameter of the chosen fluorescent particles is of the order of magnitude of 100 nm to 10 μm (Fig. S1), similar to that of human-exhaled droplets [24,32]. The peak excitation wavelength of the fluorescent particles is about 375 nm (Fig. S2) in the range of UV light, so the particles are invisible without the UV light and thus do not interfere with the experiments. The peak emitted light is about 433 nm and can be recorded by cameras as it is in the range of visible light.

Fingerstalls were used to represent the hands of 124 passengers in the economy class of the plane [20]. The environmental surfaces considered in the study were porous (126 seatbacks, made of Dacron) and non-porous (126 tray tables, 168 armrests, and 2 toilets made of modified propylene polymer). Due to space limitations, all these surfaces were shrunken from that in the real plane at a specific proportion (5.17:1), which is about the ratio of hand length to fingertip length.

2.2. Measurements of transfer efficiencies

The transfer efficiencies of the fluorescent particles were measured as the input parameters for the simulations to avoid errors caused by the different transfer properties of fluorescent particles and virus-laden aerosols. As the transmission process could be highly influenced by finger touching forces [33], the transfer efficiencies were investigated with different touching forces.

As the first step, the range of touching forces was determined. An ordinary balance (SF-400, SIQI, Jinan, China, capacity: 7000 g, readability: 1g) was touched by fingers 1000 times and the reading for each was recorded. The balance can reflect the pressure, enabling the touching force to be estimated.

The transfer efficiencies were measured using a homemade touching machine, as shown in Fig. 2. The device can specify the touching force and control the contacting duration as required. Three kinds of surface materials are typically used in the benchtop experiments. As such, four kinds of transfer efficiencies, i.e., from plastic pieces (modified propylene polymer) to fingerstalls, from fingerstalls to plastic pieces, from Dacron pieces to fingerstalls, and from fingerstalls to Dacron pieces, were respectively measured.

The measurements of transfer efficiencies from plastic pieces to fingerstalls can be used as an example of the process. First, weigh a clean piece with the analytical balance (Secura125-1S, Sartorius, Goettingen, Germany, capacity: 120 g, readability: 0.01 mg) and record the reading denoted as m_1. Second, apply fluorescent particles onto the piece uniformly with a spray and then weigh the piece with the analytical balance again, with the reading denoted as m_2. Third, fix a clean fingerstall onto the touching machine and touch the contaminated piece with a given force denoted as f. Fourth, weigh the touched piece on the