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Fomite workshop recommendations addressing the role of surfaces in virus transmission in the built environment

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ABSTRACT The emergence of SARS-CoV-2 has led to a need to assess the role of fomites in viral transmission within the built environment. Assessing the role of fomites is necessary for developing intervention strategies for controlling emerging pathogens. A fomite workshop with experts was convened in November 2024 by academia, several government agencies, and public health officials to evaluate existing data and discuss how to mitigate risks. Fomite transmission is influenced by the nature of the built environment, population density and proximity, environmental factors (humidity, heat, etc.), virus survival, surface type, engineering controls (ventilation, physical barriers, etc.), and human behaviors. Based on our current data, direct contact with a contaminated surface/fomite, even for respiratory viruses, presents a risk of viral exposure and transmission by both contact with the fomite and resuspension in the air. Even respiratory viruses can be resuspended from fomites following human and pet movement, activities (e.g., vacuuming, toilet flushing, etc.), or changes in ventilation/indoor airflow. After resuspension from surfaces, microbes can be potentially inhaled (contributing to droplet and/or aerosol exposure) and/or re-deposited from primary to secondary fomites. Development of standard methods (molecular, chemical/physical, and infectivity assays) for detecting the presence of viruses on fomites and human behavior modeling would help to determine the most effective infection prevention strategies.

KEYWORDS fomites, surfaces, virus, aerosols, transmission, risk, built environment

In the modern world, we spend 90% of our time in the indoor environment, more than any generation in history (1). This includes not only homes and workplaces but also transportation (automobile rideshare, bus, subway, and air travel), shopping malls, stores, stadiums, etc. In addition, interacting with indoor environmental surfaces is heightened due to our reliance on communication and computer technology (i.e., touch screen checkout stands, ATMs, cell phones, and computers). As a result, these high-touch environments increase interactions and proximity to other people, and we experience greater exposure to pathogens via inhalation and contact with surfaces than any generation in history. Such physical interaction creates increased potential for the transmission of viruses via fomite interaction. The goal of a November 2024 fomite workshop was to better understand the potential routes for the transmission of viruses leading to better targeted hygiene strategies for controlling their spread.

EVIDENCE FOR THE TRANSMISSION OF VIRUSES VIA FOMITES

Epidemiological and laboratory studies with human subjects have demonstrated the transmission of both enteric and respiratory viruses to humans via fomites (2). Fomite

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transmission of enteric viruses is a substantial route since these viruses require ingestion for their transmission (3). However, assessing exposure becomes more complicated with respiratory viruses, where transmission can also occur by inhalation and contact of contaminated hands to the nose or eyes. Evidence suggests that respiratory viruses can be transmitted by fomites (2–5), but to what degree in any venue (i.e., offices, schools, homes, hospitals, mass transport, etc.) depends on several complex factors (Table 1).

DETECTION OF VIRUSES ON FOMITES

Detection of viable viruses and/or their genomes on fomites is useful in assessing exposures to viruses and the likelihood of transmission via probabilistic models (6). The development of molecular methods for virus detection has made quantitative exposure modeling more feasible; however, the infectivity (determined by assay in cell culture-based methods) of the virus cannot be determined by these methods (7). Unlike laboratory-grown viruses, the infectivity of naturally occurring viruses circulating in a population is difficult to assess because they may not replicate efficiently (low virion to genome ratio) or at all in cell culture, resulting in a substantial underestimation of infectivity on a surface (8). This may account for the often lack of detection of infectious viruses from fomites by culture vs detection by PCR. Further ambiguities in culture-based methods of detection arise from virus-to-cell avidity, observation errors, and limits of quantitation. Lack of standard methods and quantification of detection method efficiency for viruses on fomites are also problematic, making comparisons of different studies difficult. Lack of standard methods, variation in recovery from different surface types (9), and suspending organic matter (10, 11) can play a contributing role in estimating exposure. The occurrence of viruses on fomites is also a dynamic process, given that deposition onto indoor surfaces, die-off, and removal by individual contact or re-suspension into the air occur repeatedly over time (18). Thus, sampling of fomite contamination is only a snapshot of potential exposure at any given time (19).

FACTORS IN FOMITE-MEDIATED TRANSMISSION

Fomites may become contaminated by contact with bodily fluids either from direct contact with infected individuals or through the generation of aerosols or droplets (sneezing, coughing, toilet flushing, etc.) (1). Assessing the significance of fomite transmission is complex, as it depends on many interacting factors (Table 1). The relative role these factors play will influence the significance of fomite transmission in any venue (home vs office building vs school) and vary with the design of modern indoor environments.

Gerhardts et al. (8) suggested that dose-response and viral survival are the most important risk factors in transmission from fomites. For example, norovirus has a very low infectious dose and persists for days or weeks on environmental surfaces (3, 9). However, it is important to understand viral shedding to optimize the treatment and prevention of

TABLE 1 Factors involved in fomite-mediated transmission

Factor	Comment	Reference
Shedding rate	The concentration of viable viruses released into the environment from an infected individual. Greater shedding may occur early in the infection.	(6, 7)
Infectivity (dose-response)	How many viable virions translate to a given probability of infection in a susceptible host.	(8)
Survival of virus on fomite and the skin	Influenced by environmental conditions (e.g., relative humidity and temperature)	(6, 9)
Nature of fomite and virus	Affects both survival and transfer	(10, 11)
Nature of the viral suspension medium	Affects both survival and transfer	(12)
Frequency of fomite touching	Depends upon the venue, i.e., activities	(6)
Efficiency of transfer to an individual	Depends on the type of fomite, humidity, and degree of interaction.	(13)
Frequency of face contact	Varies with age and activities	(14)
Crowding	Number of people in a facility and degree of shared space	(6, 15)
Air circulation	Influences settling rate onto fomites and resuspension	(16, 17)

exposure, thus transmission (19). The rate of viral shedding from an afflicted individual may change during the course of an infection, resulting in varying degrees of environmental contamination over time (7).

Transmission of respiratory viruses via fomites involves several quantifiable events, as illustrated in Fig. 1. This usually involves touching or interacting with a contaminated surface and then touching the mucus membranes of the face. The probability of infection is dependent upon the percentage of transfer of the virus for each of these events and may depend on several factors, such as the nature of the surface, matrix, frequency of contact with the surface, relative humidity, temperature, and frequency of face touching. Numerous studies have attempted to quantify these events (Table 1), and they can be used as input variables in models to estimate the risk of infection (20, 21). The transfer of the virus to the fingers from hard, non-porous surfaces is believed to present the greatest risk, because of more efficient transfer than from porous surfaces (7, 19). However, surfaces can be contaminated with small particles (<5 µm) and droplets that can be resuspended or aerosolized, in addition to contamination from person-to-surface contact (direct contact) (19). The potential for resuspension (re-aerosolization) of viruses from porous surfaces may be greater than from a non-porous surface, resulting in greater contamination of surrounding fomites and increased risk of inhalation (17, 22)

DYNAMIC DISSEMINATION OF VIRUSES IN THE BUILT ENVIRONMENT

Studies have been conducted on the dispersion of virus-contaminated fomites in homes, hotels, and healthcare-built environments (3, 20, 24). These studies demonstrated the rapid movement of tracer viruses in these environments. Within 4 hours, viruses added

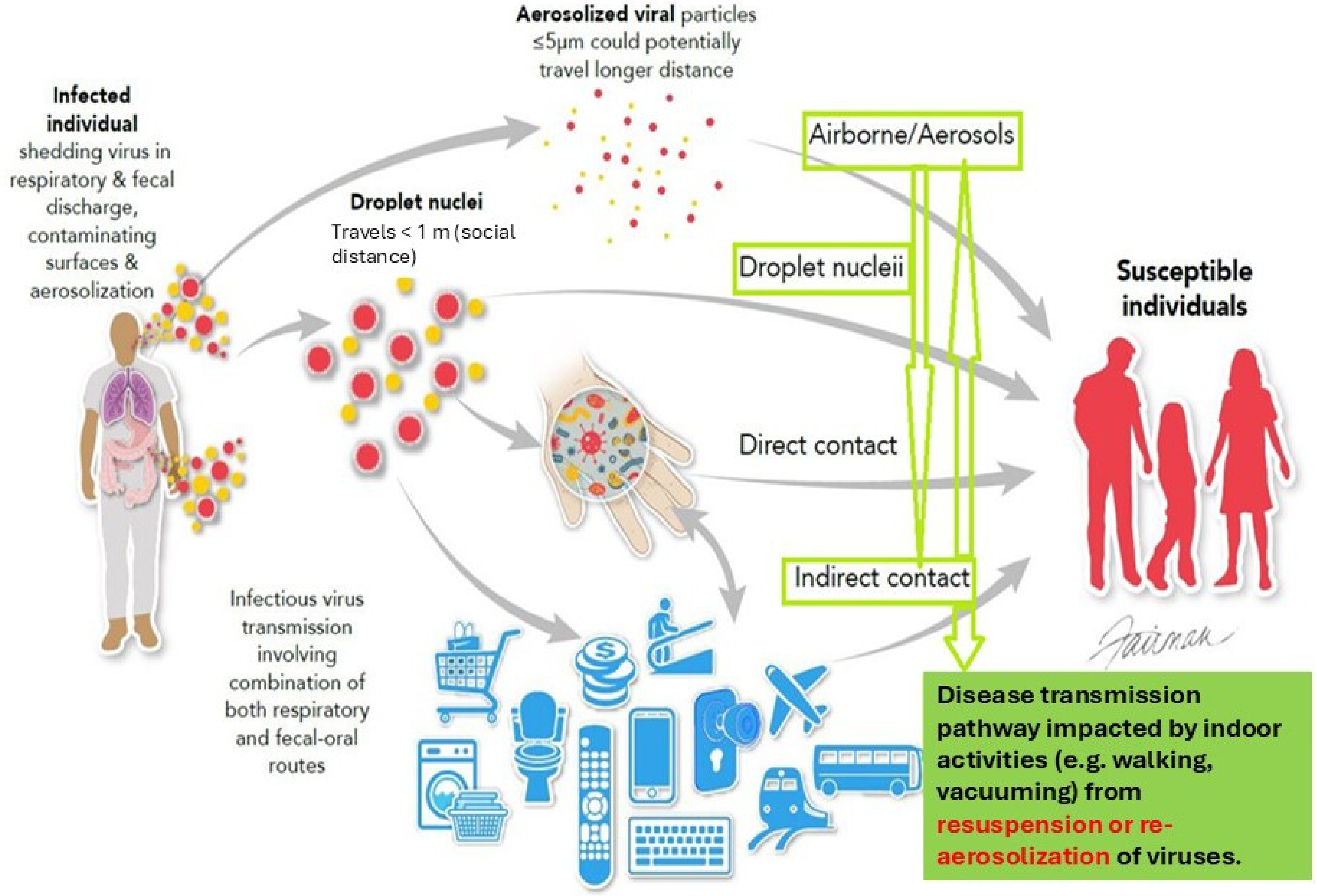

FIG 1 Virus transmission by fomites, image modified from Ijaz et al. (23); resuspension concept from Boone et al. (24).

to just one fomite or a hand can contaminate an entire built environment because of human activity throughout these spaces (20, 25). This may result from touching multiple surfaces and resuspension of viruses into the air from virus-laden surfaces. Activities such as walking or infants crawling in an indoor environment can result in the re-aerosolization of a respiratory virus from a fomite in a particle size that can be inhaled (24, 26). A similar study on contamination in an office building of just the addition of a tracer virus to the entrance door push plate resulted in the detection of the virus on half of the surfaces within 4 hours (20). Human behavior models have been developed, which demonstrate that proximity and frequent contact are important contributors to pathogen infection transmission (27). Complex behavioral networks show that people only need to touch a few items to be heavily connected to a network of transmission (28). Thus, the spread of viruses on fomites in facilities is rapid and related to human activity. Modification of the environment may also influence deposition. Wilson et al. (27), using a model, showed that the position of furniture could influence how airborne virus deposits on surfaces. Zargar et al. (29) showed that sanitizing the air reduced fomite contamination by 87%–97%.

TRANSMISSION OF RESPIRATORY VIRUSES: AEROSOLS

Models and epidemiological data suggest that fomites are a substantial route of transmission in many venues for some viral pathogens (influenza, rhinovirus, and norovirus) (6, 15). Epidemiological studies and theoretical simulation models have suggested that fomites are a main route for the transmission of virus spread via the fecal-oral route (e.g., norovirus) (3, 6). Various mechanistic modeling approaches have been used to assess the contributions of different transmission routes to the overall risk of infection. Models have been based on numerous assumptions related to human activities and virus characteristics within a specific venue. For example, in households, Nicas and Jones (30) suggested that fomites were the major route of transmission (31%) for influenza, but in contrast, Zhang and Li (31) suggested that it was a minor route (2.14%) in a student office. Varying conclusions have also been reached regarding the contribution of transmission routes of SARS-CoV-2 (5, 7, 20, 32, 33). While aerosol transmission is the major route, the degree to which fomites play a role depends on the assumptions for factors listed in Table 1 and the efficiency of viral detection from the air and fomites, as well as the characteristics of a given venue (6).

MANAGEMENT OF RISKS FROM FOMITE TRANSMISSION

Development of intervention strategies to prevent transmission in the built environment is needed. Epidemiological studies, human behavior modeling, and quantitative microbial risk assessment (QMRA) are three approaches that have been used (3, 8, 27). The advantage of behavior modeling and QMRA is that they can be done without the requirement of ill individuals or large study populations. They can also be conducted in a shorter time span and at a lower cost than epidemiological studies. Previous studies have shown that QMRA modeling can predict a plausible relationship between pathogen exposure via water, food, fomites, and adverse health outcomes (3, 33, 34). The use of QMRA allows for the assessment of intervention studies in various built environments. This approach has been used to assess the benefits of interventions, such as hand hygiene and targeted surface disinfection. QMRA can be used to determine how often disinfection is needed to reach designated sustainable risk thresholds or which hygiene protocols provide the most benefit in a particular venue (35, 36). Ryan et al. (35) determined that to reduce the risk of viral infection below 1:10,000 per year from touching a fomite, a 99.9% reduction was needed based on pathogen levels documented on fomites in various facilities.

For QMRA modeling to be most useful requires data on the exposure of individuals to a specific pathogen, which is often limited because of the cost of analytical methods and the number of samples that may need to be collected to assess exposure. Also, dose-response data for all pathogens of interest may be lacking. Data on finger transfer from fomite to hand to face are also limited by existing data and often based on non-pathogenic surrogates such as the MS2 bacteriophage. Behavioral data defining touching behavior or various activities taking place in any specific venue may also be lacking.

The use of surrogates to mimic fecal or respiratory contamination can also provide insights into the sites and surfaces where contamination occurs. An example is the use of CrAssphage, which is common in feces, to assess the sites of fecal contamination (37), or the use of bacteria commonly found in the respiratory tract (38). The use of coliphage tracers has been useful in documenting risks of infection in various venues and the impact of a reduction in exposure on the risk of infection (20, 25). The use of enveloped bacteriophages, such as Phi 6 and cauliflower mosaic virus, has also proven helpful in modeling the survival of pathogenic enveloped human viruses, such as SARS-CoV-2 (39, 40), and how the humidity and temperature of the environment impact how long the virus remains infectious on fomites. Other surrogate techniques have been used as general indicators of pathogen contamination of surfaces. Adenosine triphosphate (ATP) detection has been shown to be correlated with viral contamination and may serve as an indicator of inefficient surface cleaning (41, 42). The fluorescent gel markers can be used to evaluate surface-cleaning efficacy in facilities as another approach to improving infection control and prevention practices (43). These methods cannot, however, be used to detect the presence of viruses.

Compliance with infection prevention and control measures should also be considered in assessing intervention strategies. Mask-wearing may be effective, with the degree depending on the type of mask, in reducing inhalation, expulsion of the virus from an infected person during sneezing or coughing, and face-touching risks; however, enforcement may be difficult in public venues (6). The same has been suggested for face-touching behavior and hand hygiene.

In recent years, we have seen the development of hygiene strategies based on risk management, as developed in the 1950s and now widely used in the manufacture of foods, pharmaceuticals, and other products to achieve microbial quality assurance (44). Risk management approaches are based on the concept of reducing or eliminating exposure to a pathogen. Risk management focuses on preventing exposure to pathogens by intervening at critical points (surfaces, hands, air, etc.) in the chain of infection transmission, which is most likely to result in human exposure to harmful microbes. Although this approach, which is usually referred to as targeted hygiene, was originally adopted to optimize protection against infection, it is also now seen as the means to ensure sustainable use of resources (heat, water, detergents, microbicides, etc.) and minimize the risks of adverse effects from the use of cleaning and hygiene products (44–46).

RESEARCH NEEDS AND QUESTIONS

Some of the research needs that were identified by the workshop participants are listed below. To better assess exposure from viruses on fomites, several data limitations need to be considered, such as assessments of viral infectivity assays and efficiency of environmental sampling methods for their recovery from various types of surfaces. The application of standard methods and determination of the efficiency of these methods also need to be addressed as part of the uncertainty in the development of mechanistic models used to evaluate transmission routes. Furthermore, the venue characteristics need to be considered, as the relative risk of fomite transmission is expected to differ.

i. Standard methods for the quantitative detection of viruses on fomites, including data on the detection efficiency of naturally occurring virus infectivity. This would allow for comparison of different studies.

ii. Impact of virus resuspension from fomites on the risk of infection. This would lead to a better understanding and quantification of the potential for possible inhalation transmission and contamination of adjacent fomites (18).
iii. Impact of human behavior in different venues relative to contact with fomites. Contact with specific fomites may vary in different environments (home, office, hotel, healthcare facility, etc.) and the frequency of touch to fomites and the face (13, 20, 46).
iv. Impact of soft and porous surfaces on viral resuspension and air and fomite contamination. Soft surfaces might result in greater resuspension of viruses than hard surfaces (22–24).
v. Standard methods for the use of molecular methods for virus detection to assess exposure. This would allow for better comparisons between studies.
vi. Development of indicators to contact areas of greatest contamination (e.g., measurement of CrAssphage that are common in feces or bacteria present in secretions or on the skin). Measurement of bodily fluids such as urine or saliva is a possible option.
vii. Development of hygiene efficacy targets to achieve acceptable risk thresholds. The guideline used for the daily risk of infection for drinking water is ~1:1,000,000 (47). Is this a reasonable risk for fomites, and is this achievable? Should the target risk be different for different populations (children and elderly) or venues (home and healthcare facilities)?
viii. Determination of the safety and sustainability of disinfectants with demonstrated virucidal activity.
ix. Evaluation of hygiene protocol efficacy targets to achieve acceptable risk thresholds for different venues and populations. Immunocompromised individuals may require infection risk of infection targets that are lower than those for the general public.
x. Improved quantification of transmission routes in each venue. This would lead to a better understanding of the risk of infection. Is fomite transmission more important in certain venues than others (daycare, school, and offices) (6)? Studies on fomite contact through observational studies would be useful.
xi. Development of a risk calculator to assess where to target cleaning/disinfecting to obtain the desired benefits. Development of a calculator that could be used to determine how different interventions may change the risk of infection via fomites. Quantitative microbial risk assessment models would be useful to select sites with the greatest risk and the frequency of cleaning and disinfecting (35).
xii. Determination of the air-to-surface interface characteristics relative to virus concentrations in the air and on surfaces. The nature of the viral capsid (degree of hydrophobicity or electrostatic charge) may influence the degree of resuspension as well as the nature of the surface (48).
xiii. Impact of disinfectants that have residual action on virus reduction. Disinfectants have been developed that leave a residual for 24 hours or longer. The potential benefits over time of these disinfectants need to be determined using quantitative microbial risk assessment models.
xiv. Comparative evaluation of surrogate techniques for the correlation of viral load or removal of viral pathogens. It has been shown that the use of ATP measures of organic matter on office fomites could be correlated after cleaning/disinfecting and virus reduction (42).
xv. Quantification of the role of disinfection in reducing the risk of transmission for specific venues, considering the impact of frequency. This would aid in helping determine cleaning and disinfecting regimens to optimize the reduction of virus transmission and minimize the use of disinfectants. This could be accomplished by using quantitative microbial risk models. For example, it has been suggested

based on the occurrence of viruses on surfaces that a 99.9% reduction of norovirus is needed to reduce the risk of infection to less than ~1,000,000 per event (35).

Identification of high-touch surfaces in contact with the greatest number of individuals over the shortest time (i.e., elevator buttons in transportation facilities, handles on supermarket refrigerators, and gas pump handles) needs to be accurately quantified in addition to crowding or activities of the same space by large numbers of individuals to better quantify risks (49, 50). Crowding may also be an important factor in homes in lower-income communities where greater transmission of SARS-CoV-2 has been observed to occur (51). Approaches such as the use of QMRA and mechanistic modeling should be explored to determine the impact of the targeted hygiene approaches in various venues. QMRA can be used to develop public messages based on scientific evidence of hygiene practice efficacy and provide the basis for the development of decision tools for intervention applications based on defined risk goals.

CONCLUSIONS

Fomites can be an important source of exposure to viruses that are often considered to be indirectly transmitted, and in many built environment venues (schools, offices, healthcare facilities, homes, assisted living, mass transportation, etc.), fomites may be the dominant route of transmission. Considering the comparatively longer survival rates of viruses on fomites than in the air (1, 2, 52) and the impact of re-aerosolization from previously contaminated environmental surfaces (hard/soft), the transmission potential from fomites may be greater than from aerosols alone (7, 33, 53). Thus, virus transmission via fomites presents a longer-term risk of infection that should be taken into consideration when comparing proportionate risks of aerosols vs fomites. Therefore, we recommend that a holistic interventional approach, focusing on both contaminated surfaces and air, should be considered regarding indoor virus transmission evaluations (18, 24, 54). A better understanding of the factors and venues involved will create more opportunities for infection prevention and control measures, including targeted disinfection.

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ADDITIONAL FILES

The following material is available online.

Supplemental Material

File S1 (mSphere00927-24-S0001.docx). List of workshop participants.

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