Toilet Plume Aerosol Occupational Hazards to Healthcare Facility Workers: A Review of the Literature with Suggestions for Future Research

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Introduction

An association between inhalable aerosols produced during toilet flushing and the transmission of infectious disease has been proposed for over 50 years, but surprisingly little study has been devoted to characterizing the risk of these "toilet plume" aerosols. The purpose of this report is to summarize the available scientific literature related to this topic and to identify gaps in the current knowledge base. The report is structured to address the following questions: (1) "Do flush toilets produce potentially infectious aerosols?" (2) "Do toilet flush aerosols pose a risk for the spread of infectious disease?" (3) "What other occupational hazards may be associated with toilet plume aerosols?" and (4) "What future research is needed to further characterize the risks of occupational exposure to toilet flush aerosols"?

Do Flush Toilets Produce Potentially Infectious Aerosols?

Toilets are designed to remove human wastes by flushing the wastes away with water, the mixture of wastes and water being termed sewage. Sewage as a source of waterborne infectious disease has long been recognized, but its importance in airborne transmission is still poorly understood even though the potential for airborne transmission of sewage-related infectious disease was experimentally demonstrated by Horrocks over 100 years ago (Horrocks 1907). At that time there was debate in the British public health community concerning the potential for sewer drainage system gases to pose an infectious disease

threat in homes and hospitals. Horrocks suspended agar-filled Petri dishes in the vertical vent pipes of model and actual sewage drain systems to determine whether culturable bioaerosols would be produced by flowing sewage and subsequently transported via air in the system. Suspensions of water inoculated with bacterial cultures or with actual fecal material from a typhoid patient were used as sewage in separate experiments. In the model systems he detected airborne organisms as high as 12 feet (ft) (3.6 meters [m]) up in vent pipes even when the sewage was smoothly flowing at moderate velocity through straight runs of new piping. He observed that this smooth flow and even bursting bubbles would produce airborne microbes that could be transported substantial distances in the system air while remaining viable. In one field experiment, contaminated air was observed to travel from the drain pipe of one hospital building into the drain of an adjacent building even though “disconnecting traps” were in place to prevent such air movement. A faulty trap was subsequently found to be providing an air pathway between the second building’s drain and the sewer main to which both building drains were connected. This study was the first to clearly demonstrate the potential for disturbed sewage to produce viable bioaerosols that could be transported over substantial distances. It prompted additional work by others including Andrewes, who subsequently reported measurement of sewage organisms carried by convection currents as far as 73 ft (22.3 m) up a sewage drain vent pipe (Andrewes FW 1911).

The early studies by Horrocks, Andrewes, and others focused on the implications of sewage bioaerosols for drainage system design to protect the public health, and did not explore the associated possibility of bioaerosol production when waste was introduced to the system during toilet flushing. Research in this area was not reported until the 1950s, at which time Jessen published his book titled *Luftbårne Mikroorganismer: Forekomst og* Bekæmpelese [*Airborne Microoganisms: Occurrence and Control*] (in Danish). In one chapter, *Luftbårne Bakterier Forårsaget af Udskylning af W.C.-kummer* [*Airborne Bacteria Caused by Flushing of the W.C.*-chest] (pp. 103-117), he described his experiments exploring the potential of flush toilets of various

models and flush modes to produce bioaerosols.(Jessen 1955) He “seeded” several types of toilets with suspensions of *Serratia marcescens* (then termed *Bacillus prodigiosus*) and measured the bioaerosols produced during flushing using both settle plates (agar-filled Petri dishes with the covers removed) placed on the floor in front of the toilet and a Bourdillon slit sampler. The Bourdillon sampler is a slit impactor that draws air at a rate of 1 cubic foot per minute (cfm) (28.3 liters per minute [Lpm]) through a 27.5 millimeter (mm) long and 0.25 mm wide slit to impact on the surface of a slowly rotating agar-filled Petri dish (Bourdillon et al. 1941). Deposition occurs along a radius across the plate surface, so as it rotates a 27.5 mm wide ring of deposits is produced. Both gravity-flow toilets fed from a cistern and a pressure-valve toilet fed directly from the water distribution system were examined. Residential pressure-flush toilets of the same model located on the ground and first floor of a residence were seeded with 20 mL of a “weak red suspension” of *S. marcescens*, and settle plates were placed 10-15 centimeters (cm) apart to cover a wedge of area in front of the toilet roughly $\pm$ 30 degrees from the toilet centerline. The Bourdillon sampler inlet was placed in front of the toilet at a height of 150 cm above the floor. This was well above the height of the toilet rim, which was 43 cm above the floor. Sequential air samples were collected for 2 and 6 minutes (min), for a total of 8 min, at a flow rate of 1 cfm. Marks on the Petri dishes allowed the resulting colonies to be grouped in 30-second (sec) air sampling intervals, beginning when the toilet was flushed. Colonies were found on all of the settle plates from both the 2-min and 6-min samples in both locations. Air samples indicated average concentrations of 25 and 16.7 colony-forming units per cubic foot (CFU/ft^3) for the 2-min and 6-min samples at the ground floor location and 31 and 19 CFU/ft^3 for the corresponding samples at the first floor location, but since the initial bowl water microbial concentrations were not quantified and the room sizes were different (2.8 vs. 7.7 m^3) it is not possible to directly compare the two trials. Of special interest is the finding that culturable particles were still being captured from the air 8 min after the flush at a height of 150 cm above the floor, indicating collection of “droplet nuclei” bioaerosols. Droplet nuclei are the tiny particles that remain after the

water matrix of a larger aerosol droplet completely or partially evaporates. In the case of a droplet containing one or more microbes, the microbe or cluster of microbes as well as any non-volatile residues will make up the droplet nucleus bioaerosol particle. These particles are so small that they have negligible settling velocity under gravity, and will remain airborne and travel with natural air currents (Wells 1934). Similar experiments with four models of gravity-flow toilet fed from either a high cistern located approximately 170 cm above the toilet bowl (3 models) or a low cistern mounted close to the bowl (1 model) also demonstrated the presence of culturable droplet nuclei bioaerosol up to at least 6 min after the flush. The high-cistern models also appeared to produce substantially greater concentrations of droplet nuclei aerosol than the low-cistern model, and Jessen observed that the energy of the flush appeared to have an influence on the amount of aerosol produced. One of the high-cistern gravity-flow models was noted to have a “particularly sharp” water rush during the flush and to produce more visible droplets and a higher estimated total amount of aerosol than either the other gravity-flow models or the pressure-flush model. Similarly, the low-cistern model was observed to have a “less pronounced” flush and a lower estimated aerosol production. Jessen repeated his experiment with one of the high-cistern gravity-flow toilets after it was contaminated by a person with watery diarrhea and measured average droplet nuclei concentrations of 75.5 and 52.2 CFU/ft^3 for 2- and 6-min sequential samples, which included colonies believed to be *Escherichia coli* and *Bacillus fæcalis*. Jessen’s work demonstrated the potential of both gravity-flow and pressure-flush toilets to produce droplet nuclei aerosols in substantial quantities, as well as the ability of these bioaerosols to persist in the room air and remain viable for at least 6-8 min. His results also suggested a direct influence of flush energy on droplet and droplet nuclei aerosol production during a flush.

Shortly after Jessen’s book was published, Darlow and Bale acknowledged his work and suggested that “Apart from explosive exhalations such as coughs and sneezes, the commonest process predisposing to the formation of infective aerosols must surely be the flushing of a water-closet”

(Darlow and Bale 1959). They noted that any process involving splashing and frothing of a liquid will produce droplets that will subsequently “fall out” due to gravity or evaporate to form droplet nuclei that remain airborne. Darlow and Bale further noted that if the liquid is a suspension containing infectious microorganisms, then potentially infectious droplet nuclei aerosols may be anticipated. By that time these phenomena had become well recognized due to the work of Wells and others regarding droplet evaporation (Wells 1934) and the persistence, long-range transport, and infection risk of droplet nuclei microbial aerosols (Wells and Stone 1934;Wells and Wells 1936). Darlow and Bale seeded a “wash-down” type toilet with suspensions of *S. marcescens* and used liquid impingers and a Bourdillon impactor to collect three sets of 2-min air samples in the airspace above the toilet during the 12-min period immediately following a flush. A wash-down toilet is similar to toilets used today in that flush water is released from the toilet rim, flows down the bowl walls, and washes the waste into the S-shaped exit channel (Blair 2000). Bioaerosol concentrations as high as 2000 CFU/ft^3 were measured by slit impactor air samples collected in front of the toilet immediately after the flush, whereas samples from 120 cm above the toilet averaged only 20 CFU/ft^3. Samples collected at these same locations 5-7 min after the flush averaged 14 and 6 CFU/ft^3, respectively. These results were consistent with the expected presence of high concentrations of large droplet aerosol in the immediate vicinity of the toilet just after the flush, followed by concentration reduction due to droplet fall-out or evaporation to form droplet nuclei, with subsequent dispersion of droplet nuclei into the surrounding room air. This pattern had also been observed by Jessen (Jessen 1955).

Darlow and Bale also examined the clearance efficiency of their toilet’s flush and the potential for generating bioaerosol when flushing the toilet a second time without re-seeding. The 2-liter (L) (0.53-gallon [gal]) volume of water in the toilet bowl was flushed with 9 L (2.4 gal) of flush water from a low-level cistern described as producing little frothing compared to toilets with high-level cisterns. A notable result was that although bowl water samples collected before and after the flushes indicated over 99 percent reduction in water microbial concentrations

with each flush, air samples collected immediately after the flushes indicated only 50-60 percent bioaerosol reductions. The authors concluded that this result was at least partially attributable to a reduction in the number of bacteria per droplet rather than a reduction in the number of droplets containing bacteria, with each droplet producing only one colony when deposited on a slit impactor agar plate. Their intuition has since been mathematically supported by the work of Raabe, who modeled the incorporation of suspension particles in aerosol droplets as a Poisson probability process (Raabe 1968). The findings of Darlow and Bale confirmed those of Jessen regarding the potential for toilet flushing to produce droplet nuclei bioaerosols that would remain airborne for substantial periods (at least 15 min in this case) and move with air currents in the space. They also demonstrated the generation of bioaerosols during multiple flushes following an initial contamination.

Wash-down toilets were an older technology even in the 1950s, and were being replaced by siphonic toilets. Siphonic toilets feature a submerged jet that propels the waste into the outlet and initiates a siphon action that clears the wasted from the S-shaped channel. A secondary and lesser water flow passes through perforations in the rim to rinse the bowl walls during the flush. Darlow and Bale speculated that siphonic design toilets might produce less aerosol than wash-down type toilets due to their lower turbulence during flushing, which prompted Bound and Atkinson to compare the bioaerosol production of wash-down and siphonic toilets (Bound and Atkinson 1966). The flush volume was 7.5 L (2 gal) for both units. The toilet water was seeded with *E. coli* culture and air samples were collected for 5 min at seat height (50 cm) and 40 cm from the front edge of the seat immediately after flushing using a slit impactor (presumably the Bourdillon sampler in common use at the time). Both toilets were shown to produce culturable *E. coli* aerosol, with the siphonic design producing approximately 1/14th as much bioaerosol as the wash-down design for the same flush volume. Because the sampler placement (level with and in front of the toilet seat) and sampling period (immediately after the flush) virtually assured collection of large droplets that would be expected to quickly fall out under

gravity, the results do not allow comparison of the toilets regarding production of droplet nuclei bioaerosols.

Newsom seeded British toilets with homogenized feces or suspensions of various bacteria and conducted air sampling immediately after the flush using a Bourdillon slit impactor (Newsom 1972). One toilet had either a 4 ft or 12 ft (122 or 366 cm) high cistern (possibly 10 ft [305 cm] – the article lists both values). The flush volume was not provided but the cistern volume was stated to be 10 L (2.6 gal). The other toilet's characteristics were not described, nor were the locations of the air sampler relative to the toilets indicated. Both toilets were shown to produce bioaerosols as measured by both settle plates and the slit impactor. As also seen by Jessen, flush energy as determined by cistern height appeared to influence flush aerosol production, with the high-cistern toilet producing substantially more large-droplet aerosol than the lower-cistern model. In agreement with Darlow and Bale, at least a 99 percent reduction in bowl water microbial concentration per flush was seen.

The work of Jessen took place in Denmark and that of Darlow and Bale, Bound and Atkinson, and Newsom took place in England. The first reported study using an American brand of toilet was that of Gerba et al. (Gerba et al. 1975). This was a siphonic gravity-flow residential toilet with a 20-L (5.3-gal) reservoir tank presumably mounted on the rear of the bowl, i.e. "close-coupled", and had a 13.7-L (3.6-gal) flush volume and a 3.5-L (0.93-gal) bowl water volume. It was seeded with *E. coli* and three sequential sets of 50 settle plate samples were taken using open agar-filled culture dishes arrayed on the floor around the toilet. Each set of plates was exposed for a 2-hour (hr) period for a total of 6 hr of sampling after flushing. For the first 2-hr period bacteria were usually cultured only on plates from a limited area around the toilet, whereas in the later samples the positive samples were more randomly distributed around the room. This was consistent with an initial deposition of large droplets close to the toilet immediately after the flush, followed by dispersion and mixing of the droplet nuclei into the room air with delayed deposition on more distant plates as air currents randomly brought them in contact with settle plates throughout the

room. These results demonstrated the potential for aerosolization of *E. coli* by a gravity-flow American toilet during flushing. Further, the presence of cultures on settle plates exposed 2-4 hr after the flush demonstrated the persistence of viable airborne *E. coli* bioaerosol for 2-4 hr after the flush. Gerba et al. also examined the clearance of microorganisms from the bowl water during sequential flushes after initial seeding. They observed clearances of greater than 99.9 percent with the first flush for both *E. coli* and MS2 bacteriophage, but generally much lower clearances during subsequent flushes. They suggested that this difference might be due to attachment of organisms to the bowl surfaces. They also demonstrated greater clearance of *E. coli*, but not MS2 bacteriophage, when a surfactant was added to the bowl water.

In another recent study of modern toilet designs, Barker and Bloomfield seeded a British residential gravity-flow toilet with *Salmonella enteritidis* PT4 in semisolid agar (Barker and Bloomfield 2000). In their approach the suspension was injected from toilet seat height using a syringe to simulate the force and splashing effects of acute diarrhea. A 500-L air sample was collected over a 5-min period immediately after flushing using a perforated plate jet-to-agar microbial air sampler, but the authors neglected to indicate its placement. The flush volume for the toilet was also not stated. In three trials, *Salmonella* was cultured from only one air sample and indicated an air concentration of only 1 CFU/ft^3. However, the authors noted the generation of visible droplets and detected *Salmonella* contamination on the top and underside of the toilet seat and the underside of the toilet seat lid. They concluded that droplet bioaerosols were produced during flushing and subsequently settled on toilet and bathroom surfaces. This result was similar to that of Hutchinson, who demonstrated toilet seat contamination with *Shigella* after flushing contaminated toilets (Hutchinson 1956), and was consistent with other previous works as well (Jessen 1955;Hutchinson 1956;Darlow and Bale 1959;Newsom 1972;Gerba et al. 1975;Bound and Atkinson 1966). Of more interest was their detection of the organism in biofilm below the bowl waterline for 50 days after the seeding, at which time the toilet was disinfected with bleach. It was also detected in biofilms

growing in moist areas above the waterline, such as below the rim. *Salmonella* was also found in the bowl water after 12 days, suggesting a possible role of biofilm as a long-term reservoir and active source of pathogenic organisms in the bowl water.

Yahya et al. examined the influence of surfactant content of disinfectant-free continuous release toilet bowl cleaners on bioaerosol production during sequential flushes of a toilet (Yahya et al. 1992). Three commercially available products were used, with surfactant content of 18.2, 6.7 and 2.5 percent. These were designed for mounting under the bowl rim in order to release the product during each flush. The gravity flow toilet had a 20-L (5.3-gal) tank volume, 3.5-L (0.92-gal) bowl volume, and 14-L (3.7 gal) flush volume, and was seeded with *E. coli* culture to an initial concentration of 10^6 colony-forming units per milliliter (CFU/mL) of bowl water. Agar-filled Petri dishes were suspended over the bowl in inverted position and facing the water. Settle plates were also placed on the floor around the toilet and exposed for 3 hr after each flushing. Water samples collected before and after flushes showed average reductions in *E. coli* concentration of approximately 99.9 percent regardless of the surfactant used, with a general first-flush trend of increasing clearance with increasing surfactant concentration. In contrast, clearances were much lower for the second and third flushes for all conditions, as also seen by Gerba et al. Yahya et al. also found that the number of colonies observed on plates suspended over the bowl decreased substantially with increasing surfactant concentration. Compared to the no-cleaner condition, ejected droplet aerosol measured on the inverted plates decreased by approximately 20, 65, and 83 percent for the 2.5, 6.7, and 18.2 percent surfactant, respectively. Approximately 45 percent fewer colonies were observed on the settle plates when cleaners were used, compared to no cleaner, but there was little or no difference between cleaners. The authors concluded that the decrease in plate counts was probably due to the surfactant's effect of reducing the bowl water surface tension, but specifically how this change might have influenced the droplet number, size distribution, or capacity to carry microbes was not discussed. Though the effects of surface tension on the

number and size of droplets formed during atomization, splashing, turbulent flows, and other fluid processes including toilet flushing are not clearly understood, Mercer's work with air jet nebulizers suggested that droplet size should decrease as surface tension decreased (Mercer 1981). If so, a corresponding downward shift in particle size distribution would be expected to reduce the number of large droplets ejected during a flush and could account for the observed pattern of decreasing plate count with increasing surfactant concentration.

Barker and Jones explored the relative contributions of bowl wall and bowl water contamination on toilet bioaerosol production, as well as the effects of sequential flushing (Barker and Jones 2005). They seeded a British domestic toilet in a residential bathroom with *S. marcescens* or MS2 bacteriophage in semi-solid agar suspension to simulate loose stools. Experiments were conducted with only the sidewalls contaminated (*Serratia*) and with both the sidewalls and water contaminated (*Serratia* or MS2). The bathroom had a volume of 2.6 m^3 (92 ft^3), and the toilet had a 12-L (3.2-gal) flush volume and 2-L (0.53-gal) bowl water volume. Air samples were collected immediately after flushing using a jet-to-agar impactor sampler positioned 30 cm in front of the toilet at a height of 20 cm above the toilet seat, with the toilet seat lid open. They also exposed agar-filled settle plates for 30 min after each flush at each of 5 locations around the toilet, including on a shelf behind the toilet at 83 cm height above the seat, and on top of the cistern at 41 cm above the seat. Impactor air samples demonstrated the presence of bioaerosols at 1, 30, and 60 min after flushing for both the sidewalls-only and water-and-sidewalls contamination conditions with *S. marcescens* and for the water-and-sidewalls contamination with MS2. There was no significant difference in bioaerosol concentrations produced by applying the seed suspension to the sidewalls as opposed to directly to the bowl water. Airborne MS2 concentrations decreased roughly 90 percent per 30-min interval, with mean concentration after the first flush of approximately 69 plaque-forming units per cubic foot (PFU/ft^3). Airborne *S. marcescens* concentration also decreased approximately 90 percent per interval,

with mean concentration after the first flush of approximately 39 CFU/ft^3. Settle plate results were positive for all conditions and all sampling locations, including those well above toilet seat height. The plate counts were highest for those placed on the seat, but those from in front of the toilet and on the shelf and cistern top were not much lower, suggesting a substantial contribution of droplet nuclei to the counts over the 30-min exposure period.

Barker and Jones also examined the bowl water microbial clearance with each flush and the relative decrease in bioaerosol produced during sequential flushes without reseeding. Their results were similar to those of Darlow and Bale, Newsom, Gerba et al., and Yahya et al. in that they found that bowl water microbial concentrations were reduced by greater than 99 percent with each of three flushes but that the associated bioaerosol concentrations were reduced by only approximately 60 percent. Also in agreement with Gerba et al. and Yahya et al., they noted slightly lower clearances for the second and third flushes than for the first flush. They attributed this difference to the effects of sidewall contamination.

The limited effect of reduced bowl water microbial concentrations on reducing bioaerosol production during sequential flushes was also illustrated in the work of Scott and Bloomfield, who examined the effect of various cleaning and disinfection procedures on environmental contamination from college and hospital toilets in Britain (Scott and Bloomfield 1985). Their field study involved surface and air sampling for microbial contamination of toilet water, toilet surfaces (bowl, rim, seat, flush handle), nearby floor surfaces, and the restroom air. The compared conditions were daily cleaning without disinfectants, daily cleaning with disinfectants (hypochlorite in college toilets and quaternary ammonium in hospital toilets), and daily cleaning plus continuous disinfection via slow release chlorine blocks suspended in the toilet cistern. Although daily disinfection somewhat reduced the observed bowl water contamination compared to daily cleaning without disinfection, continuous disinfection was far more effective in both the college and hospital environments, and especially in the hospital. For direct cleaning without disinfectants, at least 95 percent of

college and hospital bowl water samples exceeded 10 CFU/mL, whereas with continuous disinfection only 5 percent exceeded this value. Nevertheless, settle plate air samples exposed for 4 hr showed no consistent reduction in CFU/plate to correspond to the reduction in water contamination. The frequency of high count plates was actually higher with continuous disinfection in the hospital. The authors concluded that the limited reduction in contamination in air and on toilet and nearby surfaces suggested that a substantial proportion of the contamination around the toilet occurred by direct shedding or transfer from users rather than via the toilet. However, this result is also consistent with the findings of Darlow and Bale and Barker and Jones showing that reductions in bowl water contamination should not be expected to produce a proportionate decrease in the bioaerosols generated during a flush.

The experiments of Barker and Jones demonstrated the generation of bacterial and viral bioaerosols during flushing of a standard domestic toilet (Barker and Jones 2005). They also demonstrated the ability of these bioaerosols to be transported well above the bowl top, to at least a height of 83 cm above the seat. This was in agreement with the results of Jessen and Darlow and Bale. The impactor samples collected 30 and 60 min after the flush indicated the production of droplet nuclei bioaerosols able to remain airborne and viable for extended periods, in agreement with Jessen and Gerba et al. Sequential flushing without re-seeding continued to produce bioaerosols in concentrations only moderately reduced from that produced by the first flush after heavy contamination, in spite of 90-99 percent clearance of microbes from the bowl water with each flush, again in agreement with Darlow and Bale.

Prior to the mid-1990s, U.S. toilets typically had flush volumes of approximately 3 to 3.5 gal (11 to 13 L), but since the Federal Energy Policy Act of 1992 the maximum flush volume allowed for toilets sold in the U.S. is 1.6 gal per flush (gpf) (6 L per flush [Lpf]) (United States Congress 1992). In recent years water conservation concerns have prompted greater marketing of high efficiency toilets, or HETs, in the U.S. While U.S. federal law limits toilets to 1.6 gpf (6 Lpf), U.S. EPA WaterSense-certified HETs are further limited to no more than 80

percent of this volume or 1.28 gpf (4.8 Lpf) (United States Environmental Protection Agency 2011). Another water-saving innovation was the introduction of dual-flush toilets providing for user selection of a low or high flush volume, depending on whether urine only or solids were being flushed. The first dual-flush toilets were invented in Australia 30 years ago and have long been in widespread use in Australia and Europe, but have only recently been widely marketed in the U.S. O'Toole et al. reported their inability to detect aerosols or droplets produced by a dual-flush toilet operating at 3 or 4.5 Lpf when measured using a time-of-flight aerodynamic particle sizer and a scanning mobility particle sizer (O'Toole et al. 2009). They were able to detect 2-3 micrometer (µm) diameter particles 5 cm above the toilet and 0.2-1 µm particles at 42 cm above the toilet when the flush volume was increased to 9 L. O'Toole et al. were measuring aerosol produced from clean water only, and concluded that the absence of organic content in the water would significantly impact the aerosolization of microorganisms. However, water droplet aerosols are difficult to measure accurately because of their rapid evaporation and the limitations of real-time aerosol measurement techniques, as experienced by Baron and Willeke while attempting to characterize droplet aerosols produced by heated whirlpool baths (Baron and Willeke 1986). The results of O'Toole et al. are of limited utility in assessing the potential for droplet nuclei bioaerosol production because the toilet was not seeded with a microbial suspension.

It may be concluded from the peer-reviewed studies discussed above that flush toilets of various designs spanning at least 50 years of production in Europe and the U.S. have been shown to produce substantial quantities of aerosol, that these aerosols are capable of entraining microorganisms at least as large as bacteria, that such bioaerosols will be produced during multiple flushes after toilet contamination, that sufficiently small microbe-laden droplets will evaporate to form droplet nuclei bioaerosols the size of which can be consistent with that associated with respirable penetration, and that these droplet nuclei bioaerosols may remain viable in the air for extended periods and travel with air currents.

Do toilet flush aerosols pose a risk for the spread of infectious disease?

Contact Transmission Risk due to Surface Contamination by Flush Droplets

The production of both large droplet and droplet nuclei bioaerosols during toilet flushing was shown in the studies discussed above, and a number of these studies also demonstrated the associated contamination of toilet seats and lids, the surrounding floors, and nearby surfaces by these aerosols (Jessen 1955;Darlow and Bale 1959;Newsom 1972;Gerba et al. 1975;Barker and Jones 2005;Yahya et al. 1992). Since both the vomit and feces of infected persons may contain extremely high pathogen concentrations – e.g. 10^5-10^9 *Shigella* (Thomson.S. 1955), 10^4-10^8 *Salmonella* (Thomson.S. 1955), and 10^8-10^9 norovirus (Atmar et al. 2008) per gram of stool and at least 10^6 norovirus per milliliter of vomit (Caul 1994) – some fraction of the aerosol droplets produced during toilet flushing may be expected to contain microbes (Raabe 1968).

Whether toilet aerosol droplets will deposit by settling on nearby surfaces or evaporate to form droplet nuclei depends primarily on the initial droplet size and the initial vertical distance from a deposition surface. Wells' classic evaporation and falling curve for droplets predicted that droplets smaller than approximately 125 µm diameter would evaporate to droplet nuclei size before falling 2 m (the approximate height of a person), whereas droplets larger than this "critical size" would not (Wells 1934). Xie et al. refined the evaporation and falling model to include relative humidity (RH) effects, and showed that droplets evaporate more slowly at higher RH as might be expected (Xie et al. 2007). The critical size shifts downward as RH increases because the evaporation rate slows down. Solutes in the droplet liquid also influence the evaporation rate and the final particle size, though the effect is small at low solute concentrations. The Xie model predicted critical sizes of approximately 60, 85, and 125 µm at 90, 50, and 0 percent RH, respectively, for physiological saline droplets and a 2-m deposition

distance. These results were in good agreement with the available experimental data on evaporation of motionless and freely falling droplets produced by Ranz and Marshal for 0 percent RH and Hamey for 70 percent RH (Ranz and Marshall 1952;Hamey 1982). More generally, the critical droplet size for an arbitrary deposition distance will be determined by the droplet evaporation rate and the droplet's settling velocity, both of which are complex time-varying functions as discussed by Hinds and Xie et al. (Hinds 1999;Xie et al. 2007). Thus, whereas even very small toilet plume aerosol droplets produced during toilet flushing might be expected to deposit on the toilet seat, only larger droplets would reach the floor before evaporating to droplet nuclei size.

Once a pathogen-bearing droplet deposits on a surface, the pathogen may subsequently be picked up by contact and transmitted to another surface or to a susceptible host. A critical determinant of the infection risk posed by a deposited pathogen will be the organism's ability to survive on a particular surface (Boone and Gerba 2007). In their review of the persistence of nosocomial pathogens on inanimate surfaces, Kramer et al. noted that many pathogens, including *Shigella*, *E. coli*, *Clostridium difficile*, SARS coronavirus, astrovirus, norovirus, and rotavirus, can survive on surfaces for weeks or even months (Kramer et al. 2006). These pathogens may be present in vomit or stools of infected persons, and microbial contamination of toilet surfaces and surrounding areas has been suspected as a source for infectious disease transmission for some time. In 1956, Hutchinson associated the transmission of Sonne dysentery with *Shigella* contamination on toilet seats, but early environmental surveys of toilets and surrounding surfaces generally failed to identify a clear hazard for this or other pathogens (Hutchinson 1956). For example, when Newsom conducted a microbiological survey of toilet seats, flush handles, and lids in several British hospitals, he cultured few *Escherichia* bacteria from contact plates and concluded that infection from contact with hospital toilet surfaces would be unlikely unless they were grossly contaminated with feces (Newsom 1972). In contrast, when Mendes and Lynch surveyed 130 male and female washrooms and toilets in shops, offices, factories, schools, hospitals, and

other public spaces, they cultured fecal microorganisms including *E. coli*, *Streptococcus faecalis*, and *Staphylococcus albus* from over 25 percent of the toilet seats (Mendes and Lynch 2011). Toilet seats and floors were among the most contaminated areas examined, with approximately 25 percent of the seats showing contamination of greater than 1000 bacteria per square centimeter. Mendes and Lynch concluded that persons infected with *Salmonella typhimurium* or *Shigella sonnei* could be expected to contaminate toilet areas. Barker and Bloomfield surveyed toilet areas in six homes where an attack of Salmonellosis had occurred within the past two weeks but found residual *S. typhimurium* contamination only in the moist areas under the toilet rim and in the biofilm lining the bowl below the waterline (Barker and Bloomfield 2000). No contamination was found on dry areas including the toilet seats. However, when these toilets were seeded with *S. enteritidis* and samples collected immediately after the flush, the organism was recovered from the top and underside of the seat lid after each of three flushes following the initial contamination. The time elapsed between contamination and sampling was likely a contributing factor in the differences in the observational and experimental results. Recently, Giannini et al. examined the prevalence of methicillin-resistant *Staphylococcus aureus* (MRSA) and vancomycin-resistant *enterococci* (VRE) contamination of employee-only, public access, and patient-only toilet seats in a children's cancer hospital (Giannini et al. 2009). MRSA was found on 3.3 percent of samples collected twice daily from six toilets, but no VRE was detected.

Thorough cleaning and disinfection of environmental surfaces in healthcare facilities is a foundational component of infection control programs designed to protect workers as well as patients (Sehulster and Chinn 2003). Disinfection is particularly important, as many studies have shown that microbial surface contamination may persist on toilets and surrounding areas even after cleaning. Following an outbreak of *C. difficile* in a large hospital, Eckstein et al. assessed the prevalence of residual contamination on environmental surfaces including toilet seats after discharge of *C. difficile* patients (Eckstein et al. 2007). Swab samples were obtained within three days of discharge in *C. difficile* patient

rooms both before and after terminal cleaning was performed. For comparison, swabs were also collected in the rooms of patients infected with VRE, after patient discharge and terminal room cleaning by hospital staff. Their results showed that for both *C. difficile* and VRE, the majority of contaminated toilet surfaces were still contaminated after terminal cleaning. Subsequent disinfection with bleach was nearly 100 percent effective in eliminating the contamination for both organisms. When Boyce et al. sampled commonly touched environmental surfaces such as bedrails, call buttons, door handles, toilet seats and lids, bedside tables, and television remotes in rooms of hospital patients whose stools exhibited heavy growth of MRSA (cases) and also of patients infected with MRSA but whose stools were negative for the organism (controls), they found contamination in rooms from both groups (58.8 percent in case rooms, 23.3 percent in control rooms) (Boyce et al. 2007). Residual contamination from previous MRSA patients inhabiting the control patient rooms was cited as a possible source of the control room contamination, even though terminal cleaning had been performed using quaternary ammonium based disinfectants. Residual environmental MRSA contamination was also cited as a possible infection source by Hardy et al. in their prospective study of nosocomial MRSA infection in an intensive care unit, and they stressed the importance of intensive and effective environmental cleaning and disinfection measures (Hardy et al. 2006). Periodic cleaning with disinfection via either hypochlorite or quaternary ammonium was shown by Scott and Bloomfield to be more effective than cleaning alone in reducing contamination of toilets and surrounding surfaces, but less effective than periodic cleaning combined with continuous disinfection via slow release hypochlorite blocks (Scott and Bloomfield 1985).

The effectiveness of environmental cleaning in preventing transmission of viral acute gastrointestinal disease has also been an area of discussion and study in recent years due in part to widely publicized acute gastroenteritis (AGE) outbreaks on cruise ships. AGE may be bacterial in origin but is usually viral, and is frequently caused by norovirus, rotavirus, or astrovirus. The annual U.S. incidence of norovirus infection alone was estimated by Mead et al. at over 23

million cases (Mead et al. 1999), and Fankhauser et al. noted that norovirus infection was implicated in at least 93 percent of 233 AGE outbreaks in the U.S. during 1997-2002 (Fankhauser et al. 2002). The diarrhea and vomiting typically associated with AGE as well as the high viral loads in both the stools and vomit of infected persons suggest a likely role of toilets in disease transmission, via either inhalation of infectious droplet nuclei or contact with contaminated surfaces. Environmental contamination has been shown to be a major source of AGE infection on both cruise ships and military ships (Widdowson et al. 2004;Foote 2005;Riddle et al. 2006), and the cruise ship industry has been plagued with repeated norovirus-related AGE outbreaks involving large numbers of passengers and crew and at times causing cruises to be terminated (Carling et al. 2009;Cramer et al. 2006;Isakbaeva et al. 2005). These outbreaks, often during sequential cruises of a ship, have occurred in spite of aggressive sanitation efforts and a documented history of good CDC Vessel Sanitation Program inspection scores (Carling et al. 2009). This may be due in part to the apparent resistance of norovirus (Barker et al. 2004) and perhaps other viruses to cleaning and disinfection when surfaces are heavily contaminated. Gerba et al. observed that MS2 bacteriophage and poliovirus were not completely cleared from a seeded toilet even after seven flushes, and that scrubbing with or without addition of a surfactant to the water was only minimally effective in eliminating these residual organisms (Gerba et al. 1975). They concluded that viruses may be more difficult than bacteria to elute from porous toilet surfaces. The manner in which cleaning and disinfection is performed is also important in ensuring complete disinfection of surfaces, especially when surfaces are heavily contaminated (Bloomfield and Scott 1997). These observations are directly relevant in assessing occupational risks to workers in healthcare and other environments where they are likely to come in contact with persons with AGE.

Airborne Transmission Risk due to Toilet Flush Droplet Nuclei

Production of large-droplet microbial aerosols during toilet flushing, with subsequent deposition on toilet and nearby surfaces, has primary significance as a contact disease transmission hazard as discussed above. In contrast, infectious droplet nuclei aerosols pose an airborne transmission hazard. Toilets have been shown to produce microbial droplet nuclei aerosols that can remain airborne and viable for substantial periods, and these bioaerosols may linger in the vicinity of the source toilet or be transported to other areas by air currents. If subsequently inhaled by a healthcare worker or other person, the droplet nuclei bioaerosols may cause infection and disease. A review of pathogens that may be present in toilets and that can also cause infection by the airborne route is therefore of interest.

Current understanding of which organisms may pose an airborne infection risk and under what conditions has been developed primarily in the past 100 or so years and is far from complete. In 1912 Chapin reviewed in detail the available evidence for and against airborne transmission for a number of diseases including influenza, smallpox, measles, and tuberculosis, and concluded that “it may be fairly affirmed that there is no evidence that [aerial infection] is an appreciable factor [compared to contact transmission] in the maintenance of most of our common contagious diseases” (p. 314) (Chapin 1912). However, even by that time a number studies had been published that demonstrated the generation of microbial aerosols during coughing, sneezing, and talking, their persistence in the air, their airborne transport over substantial distances, and their subsequent ability to cause infection and disease. Chapin was influenced by the work of Flügge and colleagues that appeared to show that transmission by droplets would only occur within a short distance of the source (Flugge C 1898). His position may also have reflected his concern that “Infection by air, if it does take place, as is commonly believed, is so difficult to guard against, and so universal in its action, that it discourages effort to avoid other sources of danger. If the sick room is filled with floating contagium, of what use is it to make much of an effort to guard against contact infection?” In hindsight it may be seem surprising that the importance of the airborne route of infection was

not more widely recognized. This continued to as late as the 1930s (Langmuir 1961) in spite of advances in droplet nuclei infection theory (Wells and Wells 1936;Wells and Stone 1934;Wells and Wells 1936) and additional experimental work demonstrating the airborne transmission of disease (Lurie 1930;Riley et al. 1959). However, ongoing advances in microbial air sampling and analysis techniques contributed to greater understanding of aerobiology and recognition by the 1960s that droplet nuclei microbial aerosols were important in the transmission of many infectious diseases in both indoor and outdoor environments (Langmuir 1961;Cox 1987). It has since become understood that whether pathogens contained in airborne droplet nuclei actually cause infection and disease in a particular circumstance will depend on numerous factors including the organism's viability under existing environmental conditions, the size and chemical composition of the droplet nuclei matrix, the number of organisms inhaled and their virulence, and host immune status (Cox 1987).

A number of diseases are known or suspected to be transmissible by the airborne route. For some, much of the research on their potential for dispersion in aerosol, transport, and airborne survival under various environmental conditions has been conducted because of concern that they might be used as biological warfare or bioterrorism agents (Knight 1980;Franz et al. 1997;Kortepeter and Parker 1999). Most are either not transmissible from human to human or are not present in feces or vomit, and so are not relevant to the present discussion of toilet flush aerosols. Toilet-related pathogens that are of interest include those causing gastroenteritis. A number of gastroenteritis-causing bacteria, protozoa, and especially viruses will be shed in stool and may also be shed in vomit. Among the protozoa, *Giardia* and *Cryptosporidium* are important due to their presence in feces, low infective dose, and stability in the environment; however, although large droplet toilet aerosols may represent a contact transmission risk, airborne transmission via oocyst-containing droplet nuclei has not been shown for either organism (Caccio et al. 2005). Among the bacteria, Gram-negative bacteria are susceptible to drying and do not usually spread by the airborne route. The Gram-positive MRSA is an airborne infection concern in healthcare

environments, with a risk primarily to patients (Eickhoff 1994). The potential for toilet-related droplet nuclei bioaerosols to cause nosocomial infection including MRSA has not yet been assessed.

Mycobacterium tuberculosis (TB), which is neither Gram-positive nor Gram-negative, is exceptional among bacteria in that it appears to be most efficiently transmitted via droplet nuclei (Roy and Milton 2004). Due to the emergence of multi-drug resistant strains, it is a major and well recognized occupational hazard to healthcare workers as well as a nosocomial infection hazard to patients (Jensen et al. 2005). TB affects primarily the lungs, but TB bacilli can also be swallowed in sputum to infect the gastrointestinal tract (Sheer and Coyle 2003). At least 21 percent of TB cases reported in the U.S. in 2009 involved this “extrapulmonary” infection including infection of the gastrointestinal tract (CDC 2011), though perhaps less than 5 percent of all TB cases involve lower gastrointestinal tract infection (Sheer and Coyle 2003). Cordova et al. showed that TB bacilli can survive intestinal transit to be shed in stool (Cordova et al. 2010), and Lin et al. showed that the bacilli may remain viable during intestinal transit when they cultured *M. tuberculosis* from stools of patients with lower gastrointestinal TB (Lin et al. 2009). Because one of the symptoms of gastrointestinal TB is diarrhea (Sheer and Coyle 2003), there appears to be a possibility of aerosolizing infectious TB droplet nuclei in toilet flush aerosol. There have been no reports in the peer-reviewed literature to indicate whether the possibility of TB aerosolization from toilets contaminated by persons with gastrointestinal TB has yet been examined, but there are indicators that such aerosolization may be likely. *M. tuberculosis* is a lipid-rich, hydrophobic bacterium, and hydrophobic bacteria have been shown to concentrate on the surface of aqueous suspensions (Hejkal et al. 1980;Blanchard and Syzdek 1970) and to be aerosolized with even slight disturbance of liquid surfaces (Wendt et al. 1980;Falkinham 1996).

The most significant toilet-related airborne infection risks to healthcare workers are likely to be due to viruses, and perhaps the most significant of these

is norovirus. Norovirus accounts for 73-95 percent of nonbacterial gastroenteritis outbreaks, and half of all gastroenteritis outbreaks, worldwide (Atmar and Estes 2006). Although it is believed to be transmitted primarily by the fecal-oral route, it may also be transmitted in aerosol. Norovirus has a low infectious dose (Teunis et al. 2008) that allows spread through multiple means including aerosols, fomites, environmental contamination and of course person-to-person contact, is shed both before and after (sometimes long after) the symptomatic phase of infection, is resistant to inactivation, and can persist on environmental surfaces for extended periods (Glass et al. 2009;Estes et al. 2006;Atmar et al. 2008). Diarrhea and vomiting are both common with norovirus AGE, so both the use of toilets by infected persons and the disposal of feces, vomit, or contaminated materials in toilets would be likely to produce norovirus-containing aerosols.

Another important viral pathogen is the coronavirus responsible for Severe Acute Respiratory Syndrome (SARS CoV). Although SARS is a respiratory rather than gastrointestinal disease, the SARS CoV is known to be shed in both feces (Hung et al. 2004;Chan et al. 2004;Liu et al. 2004) and vomit (Liu et al. 2004). While the 2003 SARS outbreak originating in China and manifesting primarily in China, Hong Kong, Taiwan, Canada (Toronto), and Singapore (World Health Organization 2011) has been the only opportunity to study the epidemiology of this emerging disease, a number of studies have suggested that it can be spread by the airborne route (Booth et al. 2005;Olsen et al. 2003;Yu et al. 2004;Hong Kong Special Administrative Unit Department of Health 2011). Though not presently a common disease, it has demonstrated its potential for explosive spread, high mortality, and transmission within healthcare environments.

Novel influenza A virus H1N1 has demonstrated some important epidemiological features that indicate a potential for airborne transmission via toilet flush aerosols. Seasonal influenza does not normally present with diarrhea or vomiting, but Dawood et al. found that for 642 cases of H1N1 diagnosed in the U.S. in the first two months of the 2009 pandemic outbreak, these symptoms each had a prevalence of 25 percent (Dawood et al. 2009). Similarly,

Cauchemez et al. reported diarrhea and vomiting prevalence of 17 and 22 percent respectively among 938 H1N1 cases reported to the CDC as of the end of May 2009 (Cauchemez et al. 2009). Influenza is thought to be transmitted primarily though dissemination of large droplets and possibly by droplet nuclei during coughing, sneezing, talking, and aerosol-generating procedures such as entubation (Tellier 2009;Bridges et al. 2003) but has been measured in respirable-size aerosol in a healthcare and other facilities (Blachere et al. 2009;Yang et al. 2011). The virus has been detected in both stools and urine of H1N1 patients, even in the absence of significant gastrointestinal symptoms (To et al. 2010), and a potential for extended virus shedding in stool was demonstrated (Pinsky et al. 2010). It has been recommended that since many H1N1 patients have had diarrhea, the potential for fecal shedding should be considered and investigated (Dawood et al. 2009). The presence of H1N1 in vomit may exist and seems likely but no report documenting this was found. A suggestive study by Papenburg et al. noted that the likelihood of H1N1 transmission in a household was greatest for patients with both diarrhea and vomiting (Papenburg et al. 2010). Additional research is needed to determine the role, if any, of either fecal or vomit aerosol in H1N1 transmission. The results of epidemiological studies involving norovirus aerosol, discussed below, would seem to encourage exploration in this area.

Epidemiological Studies of Disease Outbreaks Possibly Related to Toilet Flush Aerosols

Epidemiological studies of disease outbreaks in which toilet aerosols may have played a role are not numerous, fewer still are specific to heathcare environments, and none allow clear distinction between transmission that may have occurred via contact with large droplets or contaminated surfaces and airborne transmission that may have occurred via droplet nuclei. This may be because, as pointed out by Roy and Milton, in cases in which the source

produces a low concentration of infectious particles, the aerosol is rapidly diluted as it moves out of the immediate vicinity of the source and the resulting epidemiologic pattern mimics that expected from large droplet spray or surface contact transmission (Roy and Milton 2004).

Hutchinson was among the first to suggest a link between toilet flush aerosol contamination of toilet surfaces and the spread of gastrointestinal disease (Hutchinson 1956). He demonstrated contamination of nursery school toilet seats with *Shigella sonnei* during flushing of toilets containing diarrheal feces, and associated this with subsequent contact spread of the disease. Ekanem et al. conducted environmental sampling during a 9-month prospective study of diarrhea in Houston day-care centers, but failed to demonstrate a significant difference in fecal contamination of toilet areas during outbreak and non-outbreak periods (Ekanem et al. 1983). They noted, however, that 91 percent of the observed diarrhea cases occurred in children less than two years of age who were still in diapers and did not use the toilets. Little can be gleaned from either of these studies regarding the potential role of toilet aerosol in airborne enteric disease transmission in more general environments. Similarly, although Koopman associated higher incidence of diarrhea and vomiting with poor toilet hygiene factors in grade 1-5 public school children in Cali, Columbia, he did not conduct any environmental sampling that would allow assessment of the potential role of toilet flush aerosols (Koopman 1978).

Widdowson et al. investigated AGE among passengers exposed to norovirus during an 8-hr international flight (Widdowson et al. 2005). During the flight 8 of 14 flight crew members experienced vomiting and diarrhea symptoms consistent with norovirus AGE. Of these, seven had vomiting or vomiting plus diarrhea and one had diarrhea only. After becoming ill the sick crew members were seated in the rear of the aircraft, where two of the three toilets were located. No episodes of diarrhea or vomiting occurred outside of a restroom. Although only about half of the passengers returned survey questionnaires, five were identified who developed probable norovirus illness 18-60 hr after

disembarkation, and cases were found to have visited a restroom significantly more often than non-cases. There were no reported indications of restroom soiling with vomit or feces, and the authors concluded that “inapparent environmental contamination” may have been an exposure source. They also concluded that since only limited transmission to passengers occurred and vomiting and diarrhea were confined to toilets, airborne “droplets” should not have circulated widely through the aircraft. However, no information was available on passenger seating or the areas served by sick crew before they were relieved, or which toilets were used by passengers and by sick crew, so it is difficult to draw strong conclusions from this report. It nevertheless seems probable, as concluded by the investigators, that the restrooms were a common source of norovirus exposure.

An epidemiological study was conducted by Ho et al. following an outbreak of viral gastroenteritis during a transatlantic passenger ship voyage (Ho et al. 1989). Questionnaire data available from 92 percent of the 1079 passengers included information on age, gender, food and beverage consumption, cabin assignment, and toilet availability. Attack rates were similar in all age groups, in both sexes, and on all four passenger decks, and illness was not associated with consumption of either drinking water or ice, with mealtime seating arrangements, or with any single meal. A case control study compared disease frequency in cabins with from 1-4 occupants either having or not having a private bathroom, and showed an increasing gastroenteritis risk with increasing number of occupants where a private bathroom was available as compared to cabins where one was not available. The incidence of gastroenteritis among those using communal bathrooms correlated significantly with the usage density of the bathrooms. It was also shown that in cabins with multiple occupants, the risk of a second person developing disease was higher in cabins where the first person had vomited, even though in no situation had the second case either assisted the ill person or cleaned up the vomit. It did not appear to matter whether the second person was actually present when the first had vomited. The authors concluded that person-to-person and aerosol routes were the likely

modes of transmission, with vomit being implicated as a source. They also concluded that contact spread was likely facilitated by use of contaminated communal bathrooms.

The Ho et al. study suggested a potential role of vomit-associated infectious aerosols in transmission of viral gastroenteritis, and this hypothesis was strongly supported by other studies. An epidemiological study by Marks et al. of restaurant diners who developed gastrointestinal illness following non-projectile vomiting by the source diner showed a highly statistically significant association between the location of the diners relative to the vomiting person and the attack rate experience of persons in that area, i.e. at each dining table (Marks et al. 2000). The attack rate was 91 percent at the source's table and 71 and 56 percent at the two adjacent tables. Rates of 50, 40, and 25 percent were observed at tables increasingly farther away, with decreasing rate at increasing distance. Food was shown not to be a source. This study appears to strongly support the likelihood of airborne transmission of norovirus by vomit aerosol in this situation, and by extension the likelihood of airborne transmissibility by flush aerosols from toilets contaminated with norovirus-containing vomit.

Epidemiological, experimental, and modeling studies of SARS are among the most compelling indicators of the potential for toilet flush aerosols to cause airborne disease transmission. A report by the Hong Kong Special Administrative Region Department of Health on the 2003 SARS outbreak in the Amoy Gardens apartment complex in Hong Kong concluded that exposure was likely due to virus-laden aerosols originating in the sanitary system (Hong Kong Special Administrative Unit Department of Health 2011). The epidemiological study revealed that the sewage drainage system was contaminated with SARS CoV when the index patient, who was suffering from diarrhea, visited one of the apartments and used the toilet. Sewer drain gases were believed to be drawn through dry floor drain U-tube traps into the bathrooms of other apartments by bathroom exhaust fans. For some apartments these droplet nuclei aerosols may have then been exhausted to a "light well" open air shaft on the outside of the multi-story apartment building and carried upward to other apartments. Prevailing

winds were thought to be responsible for carrying the infectious aerosol to nearby buildings where cases also occurred. In addition to the dry U-traps, a cracked sanitary system vent pipe may have contributed to the exposure. Supporting work included computational fluid dynamic modeling by Tsou of the air flow patterns around the Amoy Gardens apartment buildings, which concluded that wind-related pressure differences caused air to enter units on the windward side of the building, pass through, and emerge on the other side to then enter adjacent units on the downwind side (Tsou 2003). Tsou noted that bathroom windows, exhaust fans, and plumbing, as well as laundry racks, were located in the light well space, providing routes of air entrance into the adjacent apartments. Yu et al. also modeled the spread of aerosol in the Amoy Gardens housing complex during the outbreak, and their results similarly suggested an aerosol pathway from the sewage disposal system through dry U-traps in bathroom floor drains induced by bathroom exhaust fans, with subsequent exhaust to the open air light well and transport between buildings, and correlated these with the reporting of the first 187 SARS cases (Yu et al. 2004). These findings appear to provide the best explanation for the pattern of the initial 187 SARS cases in the Amoy Gardens apartments, and offer strong support for a conclusion that airborne transmission was perhaps the primary mechanism for inter-apartment disease transmission during the initial phase of this outbreak. Taken together, these studies suggest that SARS CoV microbial droplet nuclei aerosols produced from contaminated sewage and subsequently transported on air currents may be highly infectious for significant periods and over long distances. Because the infectious waste, whether feces or vomit, is most concentrated in the toilet bowl and substantial quantities of aerosol are known to be produced during flushing, it might reasonably be expected that infectious SARS droplet nuclei aerosol would also be produced during toilet flushing. To date, however, this has not been either experimentally or epidemiologically demonstrated.

No epidemiological studies of the 2009 H1N1 pandemic have conclusively shown airborne transmission of the virus via droplet nuclei, and the primary transmission mode is still considered to be person-to-person contact with large

particle respiratory droplets or contaminated surfaces (Patel et al. 2010). Studies involving confined environment exposures such as on aircraft or buses concluded that the airborne route did not appear to be an important mode of transmission (Han et al. 2009;Piso et al. 2011;Kar-Purkayastha et al. 2009;Baker et al. 2010). The striking differences in transportation-related influenza transmission seen in these studies (well under 5 percent) compared to that observed by Moser et al. on an aircraft (72 percent) (Moser et al. 1979) is likely due in part to the quality of ventilation in the enclosed spaces. Although epidemiological studies to date have not demonstrated airborne infection, two recent environmental studies measured influenza A virus in respirable size aerosols collected in healthcare facilities, day-care centers, and aircraft (Blachere et al. 2009;Yang et al. 2011). This finding, the shedding of influenza virus in stool and perhaps vomit, and the prevalence of diarrhea and vomiting in Novel H1N1 patients, encourage exploration of the potential for toilet flush aerosols to produce infectious virus-containing droplet nuclei aerosols.

What other occupational hazards may be associated with toilet plume aerosols?

In addition to the infectious disease transmission risk previously discussed, toilet plume aerosols may also pose an occupational risk of exposure to hazardous drugs, including antineoplastic and other cytotoxic agents, hormonal agents, immunosuppressants, antivirals, and monoclonal antibodies (Connor and McDiarmid 2006). Patients receiving treatment with hazardous drugs may excrete the parent compound or its metabolic byproducts in their urine, feces, vomit, saliva, or sweat. Greatest excretion typically occurs in urine during the first 24-48 hours after treatment, though excretion in urine and feces can continue for a week after administration (Cass and Musgrave 1992;Heggie et al. 1987;Daughton and Ruhoy 2009). “Hazardous drugs” as defined by the National Institute for Occupational Safety and Health (NIOSH) are those that exhibit one or more of the following characteristics in humans or animals:

carcinogenicity; teratogenicity or other developmental toxicity; reproductive toxicity; or organ toxicity at low doses (NIOSH Drug Hazardous Drug Safety Working Group 2004). This is a slight modification of the definition originally developed by the American Society of Hospital Pharmacists (ASHP) (American Society of Hospital Pharmacists 1990). A sample list of 157 drugs that NIOSH recommends be handled as hazardous was published in 2010 (NIOSH Drug Hazardous Drug Safety Working Group 2010) as an update of Appendix A of their 2004 *NIOSH Alert: Preventing Occupational Exposures to Antineoplastic and Other Hazardous Drugs in Health Care Settings* (NIOSH Drug Hazardous Drug Safety Working Group 2004). Of these, over half (88) are antineoplastic agents, including at least 8 that are classified by the International Agency for Research on Cancer (IARC) as Group 1 Known Human Carcinogens (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans 2011). Connor and McDiarmid noted that the nearly 100 antineoplastic drugs in current use include at least 25 known (IARC Group 1) or probable (IARC Group 2A) human carcinogens, as well as 45 that are listed as U.S. Food and Drug Administration (FDA) Pregnancy Category D (clear evidence of risk to the fetus but benefits may outweigh risks) and 5 that are listed as Category X (clear evidence of risk of abnormalities in the fetus, and the risks outweigh the potential benefits) (Connor and McDiarmid 2006). The potential therapeutic benefits of hazardous drugs outweigh the side effects that may be suffered by the patients, or they would not be approved for use; however, hospital pharmacists who prepare the formulations, nursing staff who administer the drugs to the patients and care for them afterwards, and nursing assistants, cleaning and laundry staff, and other support personnel who come in contact with the patient, patient environment, or contaminated materials may also be at risk for ill effects.

Occupational exposure of healthcare staff to antineoplastic and other hazardous drugs has been a concern and area of study since 1979, when Falck et al. reported evidence of mutagenicity in the urine of nurses who prepared and administered antineoplastic drugs (Falck et al. 1979). Various studies have suggested an association between occupational exposure to hazardous drugs

and risk of cancer (leukemia, liver, bladder), reproductive effects (spontaneous abortions, congenital malformations, stillbirth, ectopic pregnancy, infertility), and acute toxic effects (hair loss, headache, respiratory tract irritation, allergic rash and asthma, gastrointestinal upset) (see for example the discussions by NIOSH, Connor and McDiarmid, and Polovich (NIOSH Drug Hazardous Drug Safety Working Group 2004;Connor and McDiarmid 2006;Polovich 2004)). The Occupational Safety and Health Administration (OSHA) published its first guidelines on safe handling of antineoplastic drugs in 1986 (Yodaiken and Bennett 1986) and currently provides guidance on controlling occupational exposure to hazardous drugs in Section VI of its OSHA Technical Manual (Occupational Safety and Health Administration 1999). Rigorous adherence to protective measures including use of personal protective clothing and equipment, engineering controls such as Class II biological safety cabinets and closed infusion systems, and appropriate work practices has greatly reduced the levels of occupational exposure during the preparation and administration of hazardous drugs compared to 20 years ago, but exposures still occur.

Occupational exposure to antineoplastic and other hazardous drugs may occur by inhalation, dermal absorption, hand-to-mouth ingestion, or even direct injection by needle stick (Connor and McDiarmid 2006). The route of greatest influence will vary with the particular drug formulation and work task, and the exposure may be direct as during preparation and administration or indirect through contact with patient excreta or contaminated materials or environmental surfaces. The following discussion focuses on the potential for indirect exposure via toilet plume aerosols.

Patients treated with hazardous drugs can excrete the drug or its metabolites in various body fluids, including urine and vomit. From the results of laboratory and field studies of bioaerosol production during flushing of microbially-contaminated toilets, it is reasonable to expect that toilet plume aerosols containing hazardous drugs or their metabolites will be produced when patient urine or vomit is disposed in the toilet. Deposition of large droplets on toilet and nearby surfaces would then be expected to produce contamination of

these areas with the potential for subsequent contact exposure or transport to other areas on shoe soles. A number of studies have demonstrated frequent hazardous drug contamination of toilet and other surfaces during disposal of patient urine (Kromhout et al. 2000;Kromhout et al. 2000;Fransman et al. 2004;Fransman et al. 2005;Hedmer et al. 2008;Meijster et al. 2006), dermal exposures of the hands, forearms, and faces of support personnel when cleaning patient toilets (Fransman et al. 2004;Fransman et al. 2005;Meijster et al. 2006), and residual contamination of toilets after flushing (Fransman et al. 2004;Fransman et al. 2005). However, no studies have yet been reported that characterized drug-containing aerosol production during the first and subsequent toilet flushes after contamination, the pattern of deposition of these aerosols, or the environmental persistence of the contamination. Therefore, the degree of environmental contamination produced during toilet flushing, the persistence of toilet contamination after flushing, and the associated occupational exposure risk of health care providers and cleaning personnel to antineoplastic or other hazardous drugs is unknown.

What future research is needed to further characterize the risks of occupational exposure to toilet flush aerosols?

Epidemiological and laboratory studies provide evidence that potentially infectious aerosols may be produced during flushing of toilets contaminated with vomit or diarrhea from infected persons. Droplet nuclei bioaaerosols may continue to be produced during multiple flushes after the contamination occurs, resulting in close-proximity exposure of subsequent uninfected users. They may also remain airborne and viable for extended periods and be transported with air currents over substantial distances to expose persons remote from the source. The studies suggest that toilet flush aerosols may play a role in the airborne transmission of infectious disease including norovirus acute gastroenteritis - an extremely common disease, SARS - a rare but potentially pandemic and frequently lethal disease, and Novel H1N1 influenza – a proven pandemic and

frequently lethal disease. However, since contact routes of transmission can seldom be completely excluded, no studies have yet been reported that clearly demonstrate or refute an airborne infection role for toilet flush aerosols for these or other infectious diseases. Thus, the significance of the airborne infection risk to healthcare personnel due to toilet flush aerosols remains largely uncharacterized. Similarly, research suggest that antineoplastic and other hazardous drugs or their metabolites in urine, feces, and vomit of treated patients may become airborne in particulate or vapor form when they are disposed in a flush toilet or when the toilets are cleaned, but no studies have yet been performed that specifically address these potential risks.

Thorough assessment of the airborne infection and hazardous chemical exposure risk posed by toilet flush aerosols in occupational settings including healthcare facilities requires additional research to address the following questions:

What are the physical properties of toilet flush aerosols?

Droplet aerosols produced from mechanical processes such as the splashing and turbulent water flows in toilets are typically of various sizes ranging from easily visible to much too small to see with the naked eye, and the frequency distribution of droplet sizes is typically log-normal (Hinds 1999). Raabe described the probability that a particular flush droplet will contain one or more pathogenic microorganisms as a Poisson process in which the determining factors are the concentration of particles (organisms or organism clusters) in the bowl water, the size of the particles (organisms or clusters), and the size of the droplet (Raabe 1968). However, if turbulence during the flush causes the formation of bubbles that rise to the water surface and burst, then bubble bursting may influence the number and size of droplets produced and the process of “bubble scavenging” may influence the number of microbes per droplet. Blanchard and others have described the “gathering” of microbes along the surface of a submerged bubble as it rises through water and the subsequent

transfer of this microbially enriched surface layer to the fine “film droplets” and larger “jet droplets” produced when a bubble bursts at the water-air interface (Blanchard and Syzdek 1972;Blanchard 1978;Blanchard and Syzdek 1971;Blanchard and Syzdek 1978). The resulting bubble burst aerosol would thus be expected to be somewhat bimodal, as was seen by Baron and Willeke when they measured droplet aerosols above a heated whirlpool agitated with jets (Baron and Willeke 1986). The jet droplets produced at the center of the burst may be projected tens of centimeters above the water surface as is typically seen during a toilet flush, and the microbial concentration of the droplets may be up to several hundred times greater than the concentration in the water through which the bubble rose. Bubble-related production of aerosols, including bioaerosols, has been studied above bodies of sea water and fresh water, and to some extent in whirlpool baths, but to date has not been explored as a possible mechanism for toilet aerosol production. Since no mechanism has been proposed for toilet flush aerosol production, this would be a completely new area of research.

The number of droplet nuclei bioaerosols produced during a flush will be determined by the number of microbe-bearing droplets smaller than the “critical size” appropriate to the particular circumstance as described by Wells and Xie et al. (Wells 1934;Xie et al. 2007). At present the initial droplet size distributions of toilet flush aerosols for various toilet types and operating modes has not been reported. Such characterizations are experimentally difficult due to the transient nature of the distribution, i.e. because the droplets immediately begin evaporating. Effective experimental approaches to measuring initial toilet flush aerosol droplet size distributions are therefore needed.

<u>How much flush aerosol is produced, and what are the toilet design or operating characteristics that most influence aerosol production?</u>

Toilets come in many designs including standard and high water efficiency models, as well as different operating modes including gravity flow, pressure-assisted gravity flow, pressure valve, and vacuum-assisted models. Different

designs of a particular type, such as the gravity flow tank models commonly used in the U.S., may differ substantially in their flow characteristics and clearing efficiency due to differences in flush volume and flow rate, bowl and drain passage shape, siphon jet and rim flow fractions, and rim configuration (perforation number, size, angle, spacing, jet velocity, etc.). Different operating modes (e.g. gravity flow vs. pressure vs. vacuum-assisted) have fundamentally different characteristics that may influence the energy, turbulence, and duration of the flush, which are likely to influence aerosol production. To date no studies have been reported that examine quantitatively and in detail the aerosol production characteristics of modern toilets of different designs and operating modes and their associated potential for producing infectious droplet nuclei bioaerosols. Studies are needed to address this gap. Assessment of the possible roles of turbulence and bubbles in producing microbially-enriched droplets would be informative in exploring the dominant aerosolization mechanisms and generalizing the results to a mechanistic model. Results from such research could become meaningful for toilet design and selection specifications applied to healthcare and similar facilities with an increased potential for infectious and/or hazardous toilet bowl content.

How persistent are flush-generated droplet nuclei bioaerosols in the air?

It is not known how long potentially infectious droplet nuclei bioaerosols produced during toilet flushing may remain viable in the air when exposed to typical environmental conditions. Survival in the air is influenced by a number of factors, including especially temperature and relative humidity (Tang 2009). For example, influenza virus exhibits greatest airborne survival and transmission under low humidity and temperature conditions (HEMMES et al. 1960;Steel et al. 2011;Lowen et al. 2008;Lowen et al. 2007). Based on their influenza transmission studies using a guinea pig model, Lowen and Palese hypothesized that these characteristics may actually influence the mode of transmission, with airborne transmission dominating during the winter season in temperate regions but contact transmission dominating spread in the tropics (Lowen and Palese

2009). The influence of air temperature and relative humidity on persistence of microbial droplet nuclei aerosols is of interest for airborne disease transmission generally; however, because toilet flush aerosols may contain organic matter from feces or vomit and these materials may be expected to influence pathogen survival, studies specific to toilet flush aerosols are needed.

Can infection be transmitted by toilet flush droplet nuclei bioaerosols?

Animal exposure studies are needed to assess the transmissibility of infectious disease by toilet flush droplet nuclei bioaerosols. A guinea pig model has been used with success by Palese, Lowen, and colleagues to study influenza transmission (Lowen and Palese 2009;Lowen et al. 2008;Lowen et al. 2007;Steel et al. 2011) and would likely be a model of choice for airborne transmission studies of droplet nuclei flush bioaerosols from toilets contaminated with feces or vomit from influenza patients. Unfortunately, no generally accepted animal models currently exist for study of the airborne transmission of either SARS or norovirus, though Bok et al. have proposed chimpanzees as an animal model for norovirus replication and immunity studies (Bok et al. 2011).

What are the airborne concentrations and dispersion patterns of flush-generated pathogenic droplet nuclei aerosols in healthcare environments?

Environmental studies in healthcare environments are needed to quantify the airborne concentrations and dispersion of toilet flush related airborne pathogens. Quantitative real-time reverse transcriptase polymerase chain reaction (qRT-PCR) analysis of air samples would be a logical approach to assessing the presence and dispersion of pathogen-containing droplet nuclei aerosols in the vicinity of toilets contaminated with the pathogen of interest. Results of such mapping studies could also inform planning for viable bioaerosol sampling or facilitate interpretation of epidemiological study data. Infectious droplet nuclei movement and the maintenance of microbial viability in an indoor space will be strongly influenced by the operating characteristics of heating, ventilating, and air conditioning (HVAC) systems as recently reviewed by Li et al.

(Li et al. 2007), and assessment of HVAC influences on movement and viability of toilet flush bioaerosols, including the control thereof, will be required.

What is the potential for exposure of health care providers and cleaning personnel to antineoplastic or other hazardous drugs due to disposal of patient excreta in flush toilets?

The urine, feces, and vomit of patients receiving treatment with antineoplastic or other hazardous drugs may be expected to contain concentrations of the parent drug or its metabolites, especially during the first days after administration. However, to date no studies have been reported that characterize the mass of drug expected to be aerosolized, the pattern of deposition of drug on environmental surfaces, or the persistence of this contamination. Studies are therefore needed to characterize how much hazardous material is aerosolized, where and in what concentrations the material will be deposited, and the subsequent risk of occupational exposure to both patient care providers and cleaning staff. The mass deposited via rapid fall-out of large droplets may be of greatest contact exposure interest, but the transportable fraction of aerosol as droplet nuclei and as vapor, with subsequent potential for inhalation exposure, should also be addressed. A number of antineoplastic drugs have a significant vapor pressure and may be present in health care environments in both the vapor and particulate phases (Connor and McDiarmid 2006;Connor et al. 2003;Connor et al. 2000;Kiffmeyer et al. 2002;Larson et al. 2003), so sampling techniques must address both. Although progress has been made on the analysis of antineoplastic drugs collected from the vapor phase onto sorbent media (Pretty et al. 2010), additional work is needed to resolve questions about the best air sampling sorbent media and sampling and analytical methodologies to use.

What interventions might prove effective in controlling toilet plume aerosols?

Intuition suggests that closing the toilet lid before a flush should prevent the escape of at least some of the toilet plume aerosol. This was seen by Darlow

and Bale, who sampled *S. marcescens* bioaerosol at toilet seat height in front of a British Standard toilet using two-stage liquid impingers and Bourdillon slit samplers, sampling with the toilet seat lid open and closed (Darlow and Bale 1959). They found that closing the lid had a reducing effect on aerosol escape, primarily for larger droplets; specifically, they found a 95 percent reduction in pre-impinger results compared to only 58 percent reduction in the second-stage impinger results. However, Bound and Atkinson noted no significant effect of closing either of two types of toilet covers (seat and lid combinations) on the bioaerosol measured at seat height in front of a British wash-down type toilet seeded with *E. coli* (Bound and Atkinson 1966), though they cautioned that because of the sampler placement they may have measured the average contamination when the lid was open but the maximum contamination when it was closed. Barker and Jones sampled *S. marcescens* bioaerosol with the lid open and closed using a perforated plate jet-to-agar impactor placed 30 cm in front of an 20 cm above the rim height of a domestic British toilet (Barker and Jones 2005). Although they provided no data, Barker and Jones stated that closing the lid had little effect in reducing the bioaerosol concentration. Sampler placement in each of these studies complicates their interpretation. The findings of Darlow and Bale regarding reduced escape of “large droplet” aerosols (the text implies that these were greater than 4 µm aerodynamic diameter) when the lid was closed during a flush encourage the hypothesis that properly designed seat/lid combinations might prove effective in limiting the escape of toilet plume aerosols from the toilet bowl during a flush. Simple and inexpensive studies could be quickly and easily performed to evaluate the efficacy of this low-tech engineering control option. Such studies might also inform discussions about whether modifications might be advisable to the current Uniform Plumbing Code specifications regarding toilet seat design and the installation of toilet seat lids on healthcare and other public facility “water closets” (IAPMO 2009) as well as a similar requirement for gap-front seat without cover for water closets specified by the U.S. Veterans Administration Master Specification section within the National Institute of Building Sciences (NIBS) Whole Building Design Guide, which is often

cited for healthcare facility design (U.S.Department of Veterans Affairs 2011). Information on the on-line NIBS Whole Building Design Guide may be accessed at http://www.wbdg.org/.

A Google® internet search of the U.S. patent literature using the term "toilet ventilation" will return over 2300 patent citations for systems designed to prevent objectionable toilet odors from escaping to room air. An early example of a mechanical toilet bowl exhaust ventilation system involving an electric fan was that of S.C. Brown in 1902, titled "Ventilator Attachment for Water-Closets" (Brown 1902). Darlow and Bale evaluated the efficacy of a toilet seat to which an exhaust slot was mounted at the seat hinges and attached to a fan that provided a "gentle air current across the bowl" (Darlow and Bale 1959). In a series of seven experiments conducted with the bowl covered by either cardboard or a closed toilet lid, air samples collected at seat level using a Bourdillon slit impactor sampler indicated bioaerosol concentrations of 0 CFU/ft^3 in four of the seven experiments and an average of less than 4 CFU/ft^3 for the other three. However, no studies have been reported that examined the effectiveness of exhaust ventilation systems during flushing with the toilet lid open, which will be the typical situation in U.S. hospitals because the toilets do not have lids. It may also be the most common situation in residential health care environments even though these toilets typically do have lids. For example, Yung-yung recently found that up to 78 percent of university students responding to a survey indicated that they seldom or never closed the toilet lid before flushing (Yung-yung 2009). Simple and inexpensive studies could also be quickly and easily performed to evaluate the efficacy of toilet bowl local exhaust ventilation system design options.

Summary and Conclusions

Contaminated toilets have been clearly shown to produce large droplet and droplet nuclei bioaerosols during flushing, and suggest that the toilet flush bioaerosols could play an important role in airborne transmission of infectious

diseases for which the pathogen is shed in feces and/or vomit. To date, epidemiological studies have been unable to distinguish between risks of contact versus airborne transmission that may result from exposure to toilet flush aerosols. The possible role of toilet flush droplet nuclei bioaerosols in airborne transmission of norovirus, SARS, and pandemic H1N1 influenza is of particular interest. Toilet flush aerosols may also play a role in contact or inhalation exposures to antineoplastic and other hazardous drugs or their metabolites, but to date no quantitative studies related to this potential exposure have been reported. Additional research in multiple areas is therefore needed to assess the occupational exposure risk posed by toilet flush aerosols in healthcare facilities.

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