

The potential role of toilets as a vector for transmission of infectious disease

Mark Jackson^{1,*}, Josh Aldred¹, Jed Canady¹, Richard Corsi¹, Jeff Siegel¹

¹University of Texas at Austin

*Corresponding email: mark.jackson@mail.utexas.edu

ABSTRACT

This preliminary work showed that aerosolization of surrogate fecal matter (coffee grounds and broth with *S. epidermidis* bacteria) from a toilet may be a significant method of disease transmission. A simple two room model showed that solely through aerosolization of feces, the probability of infection by generic airborne viruses or bacteria with a low median infective dose ($ID_{50}=1-10$ Colony Forming Units (CFU)) may be sufficient reason to take steps to minimize this transmission vector.

KEYWORDS

Toilet, Bacteria, Feces, Aerosolization, *S. epidermidis*

INTRODUCTION

There are many public places at which toilets are repeatedly flushed throughout the day. For example, waiting passengers at Portland International Airport flush each toilet an average of 200 times a day (~once every seven minutes) (BOM, 2009). Most of us are familiar with the stench that rises and the occasional droplet that lands on our clothes when we flush a toilet. The goal of this paper is to investigate whether flushing a toilet can be a significant vector for airborne transmission of bacterial and viral disease. There are three primary vectors for the transmission of infectious diseases: fomites and direct contact; large droplets ($>10 \mu\text{m}$); and droplet nuclei ($<10 \mu\text{m}$) (Hodgson, 2009). The focus of this paper will be solely on the emission of droplet nuclei from toilets in the 1-3 μm range, a typical size for many bacteria (Kowalski, 2002).

BACKGROUND

Airborne transmission of disease is generally accepted, although it may not be the primary vector for viruses and bacteria (Hodgson, 2009, Li, 2007, Li, 2004a, Li, 2004b, Morawska, 2006). For example, Gerba (1975), counted the number of sample bacteria and viruses ejected from a flushed toilet onto an overhanging collector, and showed the potential threat posed by fecal aerosolization. However, previous research has not been found that models droplet nuclei emitted from a flushed toilet and disease transmission. Previous research on this topic has generally involved the survivability of micro-organisms within toilet bowls using contaminants that model pathogen shedding of up to 10^{10} CFU·mL⁻¹ for feces (Barker, 2005), the survivability of Salmonella within domestic bathrooms and toilets (Barker, 2000), the survival of *E. coli* deposited on surfaces by airborne droplets (Gerba, 1975), and the presence of Severe Acute Respiratory Syndrome (SARS) virus in feces and urine (Abdullah, 2003). Li, et al. (2007) linked the spread of SARS in a multi-family tower in Hong Kong to organisms dispersed from bathroom exhaust.

METHODS

We first measured the number and size of particles generated by flushing simulated excrement. Using field measurements and a modification of the Atkinson & Wein (A&W) Model (Atkinson & Wein, 2008), the probability of infection of a susceptible individual was calculated. All experiments were conducted in a 5-m³ residential bathroom in residence in Dallas, Texas, USA (Figure 1).

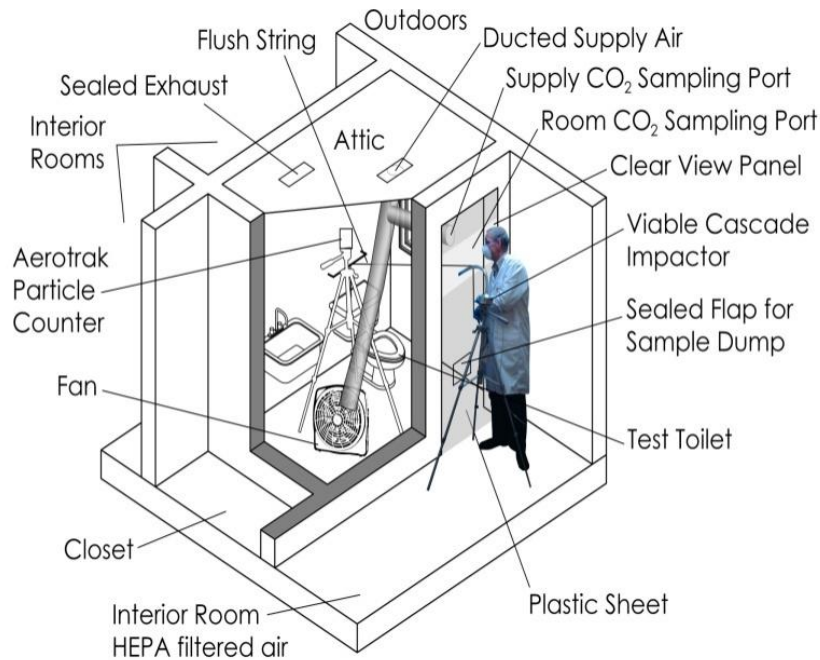


Figure 1. Diagram of Test Bathroom

The bathroom supply air was HEPA filtered and the chamber was sealed by covering the exhaust vent, window, and door with sheet plastic. A particle counter (Aerotrak Model 8220) was mounted 1.4-m above the toilet to record the number and size of particles emitted from the toilet. All paper and cloth objects were removed from the room in order to minimize sources and sinks for particles, and the room light was kept off to prevent emissions of particles from heated indoor dust (Pedersen, 2003). A small portable fan was also placed in the bathroom to help create a well-mixed testing environment. Particles were sampled over a two-hour period at 10-second ON/OFF intervals. The experiment was repeated eight times. After initiating the experiment, the room was left empty for one hour to ensure that steady state conditions returned between tests thus preventing the introduction of particles due to human movement in the chamber. Following stabilization, one cup of finely ground coffee was placed into the toilet bowl. The coffee was allowed to sit for five minutes, and then the toilet was flushed every minute for five minutes. Multiple flushes helped to create a source large enough to calculate the particle decay rate, from which the source rate could be calculated using mass balance equations for a well-mixed chamber (Equations 1-3). To minimize human presence in the room during the experiment, the ground coffee was introduced through a re-sealable flap using a cup on a long stick, and the toilet was flushed from outside the chamber using a string.

$$\frac{\partial C}{\partial t} = \lambda C_{out} + \frac{E}{V} - \lambda C - \beta C \quad (1)$$

$$L = (\lambda + \beta) * C = \frac{-\ln \frac{C(t)}{C_{max}}}{1 - e^{-Lt}} \quad (2)$$

$$S = \frac{1}{t} \int_0^t E(t) dt = \text{time-averaged emission source} = \frac{(C_{measured} - C(t=0) * e^{-Lt}) * L}{1 - e^{-Lt}} \quad (3)$$

Table 1. Definitions & units for well-mixed steady state equations

Term	Definition	Dimensions
C	Indoor Concentration	$\mu\text{g}\cdot\text{m}^{-3}$
$C_{measured}$	Measured Indoor Concentration	$\mu\text{g}\cdot\text{m}^{-3}$
C_{out}	Outdoor Concentration	$\mu\text{g}\cdot\text{m}^{-3}$
λ	Air Exchange Rate	hr^{-1}
β	Deposition Loss Rate	hr^{-1}
E	Particle Emission Rate	$\mu\text{g}\cdot\text{hr}^{-1}$
L	Loss Rate	$\mu\text{g}\cdot\text{hr}^{-1}$
S	Source Rate	$\mu\text{g}\cdot\text{hr}^{-1}$
V	Volume	m^{-3}

To further explore the possibility of disease transmission through droplet nuclei emitted from toilets, 100-mL of broth with $>10^8$ CFU·mL⁻¹ *S. epidermidis* bacteria (Microbiologics Lab, ATTC #12228) was deposited in the toilet to simulate excretion by an infected person. Staphylococcus species have diameters of 0.5-1.5 μm (Holt, 1994). Two minute air samples were collected on 100-mm Petri dishes with Tryptic Soy Agar (TSA) (Fisher Scientific) using a single-stage viable cascade impactor (SKC BioStage) at a sampling rate of 25 L·min⁻¹ at baseline, time of deposit, after the first and fifth flush, and 5, 10, and 15 minutes after the fifth flush. The bacteria were prepared by isolating a colony on growth media and growing that colony in a broth of 900-mL of Millipore water and ~27 cc of powdered TSA in a 1-L Erlenmeyer Flask autoclaved in a 16-Qt Pressure Cooker (Presto) at 15 lbs pressure for >30 minutes with confirmation using autoclave tape (Fisher Scientific). The broth was continuously stirred using a magnetic stirrer at 35 °C in a lab incubator (Fisher Scientific Model 625D). All TSA Petri dishes were grown for >48 hours at 35 °C after which resulting colonies were counted. Water samples were plated out on five Petri dishes using 1:10 serial dilutions to determine the baseline concentration of bacteria in the toilet tank, toilet bowl and broth. Air exchange rates (AERs) of the chamber were measured in triplicate using the decay rates of carbon dioxide (CO₂) created by off-gassing from dry ice. Six measurements of CO₂ levels in the supply were taken and averaged to obtain the CO₂ concentration in the make-up air (all make-up air was assumed to come from the supply). AER was obtained by using the slope of the decay curve of: $-\ln\left(\frac{[\text{CO}_2]_{\text{chamber}} - [\text{CO}_2]_{\text{supply}}}{[\text{CO}_2(t=0)]_{\text{chamber}} - [\text{CO}_2]_{\text{supply}}}\right)$ versus time.

The A&W (Atkinson & Wein, 2009) model for multiple compartment transmission of infectious disease was used to assess the probability of disease transmission from droplet nuclei emitted from a toilet. The original A&W model was based on viral shedding rates for influenza and particle emissions due to coughing and sneezing from an infected person in the household. Transmission of the virus for this paper was modeled through two compartments in a typical residential home. The end result was a probability of infection for one susceptible person who lived in the home with an infected person. The first major parameter in the model is the viral shedding rate $\chi(t)$, which varies over time and is expressed in the equations below. Where the initial median viral shedding rate is equal to the tissue culture infectious dose (TCID₅₀) and is defined as the amount of a pathogenic agent that will produce pathological change in 50% of cell cultures inoculated.

$$\chi(t) = \{A_o e^{vt} \quad \text{for } 0 < t < 24 \text{ hrs} \quad v = \text{shedding constant} = 4.94 \text{ per day} \quad (4)$$

$$\chi(t) = \{A_o e^{v(24) - \omega(t-24)} \quad \text{for } 24 \text{ hrs} < t < 144 \text{ hrs} \quad \omega = \text{shedding constant} = 1.70 \text{ per day} \quad (5)$$

$$A_o = \text{the initial median viral shedding rate} = 2.88 \times 10^7 \text{ TCID}_{50} \text{ per day}$$

The normalized viral shedding rate, $\chi(t)_n$, of particles emitted from the toilet was assumed to be the shedding rate given by A&W for coughing and sneezing to reflect the fact that infectivity of fecal particles changes over time. Each compartment is represented by a volume, V_j , and has an internal flow rate of Q_j . The parameters for the model included the bathroom volume was 5-m³ and the adjacent bedroom had a volume of 40-m³. The internal flow rate was 11 m³·hr⁻¹ and 88 m³·hr⁻¹, respectively. These values were determined by assuming an AER of 2.2-hr⁻¹ obtained in our study. The door was assumed to be open between the bedroom and bathroom throughout the model duration and the estimated flow rate between compartments was 60 m³·hr⁻¹ (assumed from A&W model).

Particle concentrations in the bedroom were calculated using a simplified version of the A&W equation for droplet transport to compartment two. The corresponding dose in compartment two was calculated by multiplying the concentration by the exposure time and integrating those values from time equals 0 to 144 hours or six days. According to the Atkinson & Wein paper, the first 24 hours is considered a viral incubation period, and the remaining five days are a period of infectious viral shedding. The integrated product was then multiplied by the breathing rate, which we assumed to be 20 m³ day⁻¹ (Atkinson & Wein, 2008). The exposure time was varied to develop a range of doses for a susceptible person in compartment two. The resulting dose was multiplied by a deposition factor g —the deposition fraction to the respiratory epithelium. A&W estimated that the deposition factor g was equal to 0.04 for a particle diameter of 1 μm (i.e. diameter of an infectious airborne aerosol). The corresponding product was multiplied by the constant α , which defined the median infectious dose for inhaled virus deposited in the respiratory epithelium. The constant α is equal to $\ln(2)/ID_{50}$. Probabilities of infection (Table 2a) per dose D were calculated using a Poisson distribution and the equation: $P = 1 - e^{-(\alpha)*(D)*(g)}$.

RESULTS

The air exchange rate (reader has forgotten what AER means) was 2.2-hr^{-1} (Standard deviation = 0.1-hr^{-1}) and the plastic sheeting bowed out indicating the chamber was under positive pressure. Airborne bacteria concentrations in the chamber are shown in Figure 2.

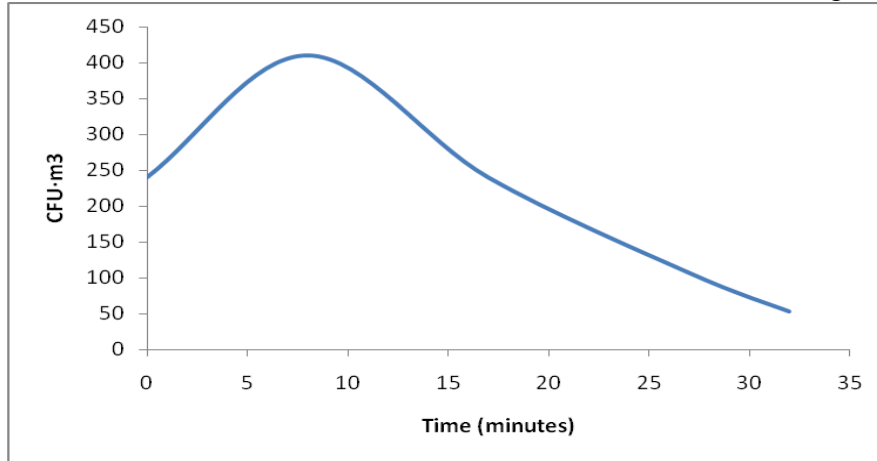


Figure 2. Airborne bacteria concentrations in bathroom after toilet flush

The resulting emission rates of $1\text{-}3\ \mu\text{m}$ particles are shown in Table 2b. Flushing the toilet gave an average particle emission rate of $0.49\ \mu\text{g}\cdot\text{hr}^{-1}$ (SD = $0.36\ \mu\text{g}\cdot\text{hr}^{-1}$). Table 2b shows the emission rate computed using equations 2 & 3 assuming a particle diameter of $1\text{-}\mu\text{m}$. Highly infectious organisms (i.e. influenza & TB) have median infective doses of 1-10 CFU, where 50% of the hosts become infected (ID_{50}) (Kowalski, 2002). The resulting probabilities of infection for disease agents at either end of infective dose range, 1-10 CFU are shown in Table 2a. For a susceptible person living and sleeping in the adjoining bedroom, it is assumed that their exposure is approximately 72 hours over the six-day symptomatic period. As a result, the susceptible person has an increased probability of infection of 94.8% due to the infectious particles emitted from the toilet in the bathroom when the toilet is used by the infected person and the bathroom door is generally left open over six days. Only one set of data for bacteria emissions from the toilet was obtained with a calculated Source Rate of $1.2\times 10^{-3}\ \mu\text{g}\cdot\text{m}^{-3}$ and a calculated Loss Rate of $8.5\times 10^{-4}\ \mu\text{g}\cdot\text{m}^{-3}$. Significantly more data is required to draw any conclusions for bacteria emissions so this paper presents detailed results only for the coffee experiments.

Tables 2a and 2b – Probability of infection to susceptible individual in bedroom (a), and particle source and loss rates (coffee) (b)

(a)

Time of Exposure (hours)	Probability of Infection (%)	
	ID ₅₀ = 1 CFU	ID ₅₀ = 10 CFU
144	99.7	44.7
72	94.8	25.6
50	87.4	18.7
36	77.3	13.8
15	44.7	5.6
8	25.6	2.9
1.5	5.8	0.6

(b)

Sample	Source Rate ($\mu\text{g}\cdot\text{hr}^{-1}$)	Loss Rate ($\mu\text{g}\cdot\text{hr}^{-1}$)
1	0.15	2.5×10^6
2	0.17	2.6×10^6
3	0.12	2.6×10^6
4	0.43	4.2×10^6
5	1.20	2.7×10^6
6	0.65	1.8×10^6
7	0.52	2.4×10^6
8	0.70	2.7×10^6
Average	0.49	2.7×10^6
SD	0.36	6.8×10^7

Without sterilizing the toilet and tank, very high background concentrations of organisms were found in the toilet bowl and toilet tank ($>4\times 10^7$ and $>2\times 10^7$ CFU·mL⁻¹). After cleaning the bowl & tank with a solution of 3% Hydrogen Peroxide (H₂O₂) in water, background levels in the bowl were reduced by 2-5 orders of magnitude to 3×10^5 CFU·mL⁻¹ to 10^2 to 10^4 CFU·mL⁻¹.

DISCUSSION

Ground coffee experiments demonstrated a significant increase in airborne particulate matter in the 1-3 μm range with deposition of coffee into the toilet bowl and subsequent flushing.

Limitations of this study include: residual bacteria levels in the toilet tank and bowl, minimal experimental bacteria runs, large variation in source rates for coffee (potentially due to non-uniform particle distribution in the coffee), and significant modeling assumptions. Enhancements for future experiments include: use of a stainless steel chamber; use of sterilized toilet, tank, and bowl to limit background emissions, temperature and humidity control; and the use of engineering controls such as putting the bathroom or toilet bowl under negative pressure.

CONCLUSION

For a simple two room model, the increase in bacteria levels (as approximated by coffee grounds) from use of a toilet were found to increase the potential for transmission of an organism with an ID₅₀ equal to 1 CFU by roughly 95%. This very preliminary work indicates the value of future and more detailed study of toilet emissions as a potential for the transmission of infectious diseases and what practical engineering controls can mitigate these issues.

REFERENCES

- Abdullah, A.S.M., Tomlinson, B., Cockram, C.S., Thomas, G.N. (2003) Lessons from the Severe Acute Respiratory Syndrome Outbreak in Hong Kong, *Emerg. Infect. Dis.*, **9**, 1042-1045.
- Atkinson, M.P. and Wein, L.M. (2008) Quantifying the Routes of Transmission for Pandemic Influenza, *Bulletin of Mathematical Biology*, **70**, 820-867.
- Barker, J., Bloomfield, S.F. (2000) Survival of Salmonella in bathrooms and toilets in domestic homes following salmonellosis, *J. Applied Microbiology*, **89**, 137-144.
- Barker, J., Jones, M.V. (2005) The potential spread of infection caused by aerosol contamination of surfaces after flushing a domestic toilet, *J. Applied Microbiology*, **99**, 339-347.
- BOM (2009) Dual-Flush Valves Curb Airport Water Usage, *Building Operating Management* Vol. February, , p. 10.
- Gerba, C.P., Wallis, C., Melnich, J.L. (1975) Microbiological Hazards of Household Toilets: Droplet Production and Fate of Residual Organisms, *Applied Microbiology*, **30**, 229-237.
- Han, K., Zhu, X., He, F., Liu, L., Zhang, L., Ma, H., Tang, X., Huang, T., Zeng, G., Zhu, B.P. (2009) Lack of Airborne Transmission during Outbreak of Pandemic (H1N1) 2009 among Tour Group Members, China, June 2009., *Emerg. Infect. Dis.*
- Hodgson, M.J., Miller, S.L., Li, Y., McCoy, W.F., Parsons, S.A., Schoen, L.J., Sekhar, C. (2009) ASHRAE Position Document on Airborne Infectious Diseases, ASHRAE.
- Holt, J.G., Krieg, Noel R., Sneath, Peter H. A., Staley, James T., Williams, Stanley T. (1994) *Bergey's Manual of Determinative Bacteriology*, 9th Ed., Baltimore, Williams & Wilkins.
- Kowalski, W.J. (2002) *Immune Building Systems Technology*, New York, McGraw-Hill.
- Lemieux, C., Brankston, G., Gitterman, L., Kirji, Z., Garden, M. (2007) Questioning Aerosol Transmission of Influenza, *Emerg. Infect. Dis.*, **13**, 173-174.
- Li, Y., Duan, S., Yu, I.T.S. and Wong, T.W. (2004b) Multi-zone modeling of probable SARS virus transmission by airflow between flats in Block E, Amoy Gardens, *Indoor Air*, **15**, 96-111.
- Li, Y., Huang, X., Yu, I.T.S., Wong, T.W. and Qian, H. (2004a) Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong, *Indoor Air*, **15**, 83-95.
- Li, Y., Leung, G.M., Tang, J.W., Yang, X., Chao, C.Y.H., Lin, J.Z., Lu, J.W., Nielsen, P.V., Niu, J., Qian, H., Sleight, A.C., Su, H.J.J., Sundell, J., Wong, T.W. and Yuen, P.L. (2007) Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review, *Indoor Air*, **17**, 2-18.
- Morawska, L. (2006) Droplet fate in indoor environments, or can we prevent the spread of infection?, *Indoor Air*, **16**, 335-347.
- Pedersen, E.K., BJORseth, O., Syversen, T. and Mathiesen, M. (2003) A screening assessment of emissions of volatile organic compounds and particles from heated indoor dust samples, *Indoor Air*, **13**, 106-117.
- Tellier, R. (2006) Review of Aerosol Transmission of Influenza A Virus, *Emerg. Infect. Dis.*, **12**, 1657-1662.
- Wein, L.M. and Atkinson, M.P. (2009) Assessing Infection Control Measures for Pandemic Influenza, *Risk Analysis*, **29**, 949-962.