APPLYING AEROSOL SCIENCE PRINCIPLES TO AIRBORNE COVID-19 VIRUS DROPLETS

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INTRODUCTION

During the last six months or so we have been inundated by the news media with countless stories, examinations and projections regarding the world-wide COVID-19 pandemic. While the US Center for Disease Control (CDC) and the World Health Organization (WHO) have provided guidance regarding personal protective equipment (PPE) and person-to-person distancing, this guidance has been politicized to a point that wearing (or not wearing) a protective face mask has become a political statement with some politicians, especially some state regulators, who have openly questioned the efficacy of any attempt at mitigating the potential of becoming infected.

While we are certainly still learning much about this highly infectious viral respiratory disease, the scientific and medical communities have reached the conclusion that, based on numerous recent events, the virus must be spreading via airborne transmission, something many public health organizations, including the WHO, have not recognized in the past [2,6,16,17,24]. In early July 2020, a group of 239 concerned scientists from throughout the world published an open letter in Clinical Infectious Diseases [20], stating:

> "Most public health organizations, including the WHO, do not recognize airborne transmission except for aerosol-generating procedures performed in healthcare settings. Hand-washing and social distancing are appropriate, but in our view, insufficient to provide protection from virus-carrying respiratory microdroplets released into the air by infected people…..
>
> We appeal to the medical community and to the relevant national and international bodies to recognize the potential for airborne spread of COVID-19. There is significant potential for inhalation exposure to viruses in microscopic respiratory droplets (microdroplets) at short to medium distances (up to several meters, or room scale), and we are advocating for the use of preventive measures to mitigate this route of airborne transmission."

All of the letter's coauthors are experienced scientists and researchers; there is a significant body of current and recent work on bio-aerosols, i.e. small particulates emitted during breathing, speaking, coughing and sneezing. There is also a large body of research on the behavior of aerosols and the design of particulate collectors such as filters, i.e. face masks. This author first developed and taught courses on the subject 40 years ago. While most of the available research has been published in the engineering or science literature, and recently in some medical journals, this body of work is seldom reviewed by the news media and not generally seen by the public.

This report will endeavor to review and explain the behavior of small droplets in air from a layman's perspective and apply our knowledge of that behavior to particulates emitted during breathing, speaking, coughing and sneezing. We will review the results of recent experimental work on bio-aerosols and their application to social distancing and PPEs. This report is not intended to provide medical advice of any kind.

BACKGROUND

In order to better understand aerosol technology, it is necessary to define the terminology used by engineers and scientist as well as the various mechanisms by which small particles settle or are collected:

Aerosols (abbreviation of "aero-solution") are a suspension of fine solid particles or liquid droplets in air or other gases. Aerosols can occur naturally such as fog, mist or dust. Man-made aerosols are particulate air pollutants and smoke. It should be noted that the use of the term "Aerosol" as it applies to small particle technology differs from the common usage where it refers to a spray that delivers a consumer product from a can or similar container.

Bio-aerosols (short for biological aerosols) are a subcategory of particles released into the atmosphere from terrestrial and marine ecosystems. They consist of both living and non-living components, such as fungi, pollen, bacteria and viruses and are typically introduced into the air via wind turbulence over a surface, including soil, water, and sewage [29]. They may also be introduced into the air by man or animals during breathing, speaking, coughing, sneezing, etc. The fact the respiratory droplets may contain pathogens has been known for more than a century [8].

Aerosol science includes the study of generating and removing aerosols, technological applications of aerosols, effects of aerosols on the environment and people, and other similar topics such as particle classification (size determination). Particle sizes within an aerosol are seldom uniform, but are generally a broad distribution of sizes. Knowing details of this size distribution is necessary in order to develop optimal collection (removal) strategies [19]. A CDC published document provides a primer on aerosol science [3].

Particle sizes in aerosols may vary widely with viruses at about 10 nanometers (nm, one billionth of a meter) to 100 micrometers (microns, µm, one millionth of a meter) for typical pollen. In comparison, human hair has an average diameter of ~50 µm, 5000 times larger than an average virus. One less known particle size phenomenon is the real size of bio-aerosols: while viruses and bacteria are much smaller than other particulates, they do tend to be absorbed on the surface of much larger liquid droplets when expelled during breathing, speaking, coughing, sneezing, etc. A further complication in predicting the behavior of bio-aerosols arises since they may become smaller or larger over time due to evaporation or condensation, depending on ambient temperature, humidity and the length of exposure to ambient conditions.

Gravity and **buoyancy** are two forces acting on all particles within an aerosol. The weight of a particle (actually defined as a downward force) is approximated by Newton's Law (1687) as the product of the particles mass times the gravitational acceleration. This downward force is opposed by an upward force, the buoyancy, which opposes the weight of a partially or fully immersed object in a gas or fluid. When the average density of particles in a gas is larger than that of the gas, they will sink, or settle. The particles' downward motion will accelerate until gravity and the buoyancy forces are equal; at that point particles reach what is defined as a **terminal settling velocity**, a constant velocity determined by the the mass of the particle and the relative density differences between it and the gas (or liquid). It is interesting to note that this last phenomenon is related to Archimedes' Principle, dating back to 212 BC; clearly, the underlying principles of aerosol science are not new or novel and have been known for centuries.

Agglomeration is a physical phenomenon particles in motion experience; two or more particles or droplets in close proximity may agglomerate and form a single, larger particle. The process has been studied extensively and correlations have been developed allowing engineers to predict the extent of agglomeration based on knowledge of the environment and the physical properties of the fluid and the particles. In practice, this process occurs mostly during **laminar flow**, a flow regime characterized by fluid and particles following smooth paths in layers, with each layer moving smoothly past the adjacent layers with little or no mixing. Agglomeration occurs mostly with small, sub-micron sized particles which generally experience very long settling times; it may be enhanced by the presence of electrostatic charges on particle surfaces. The ability to predict and enhance particle growth enables designers to predict final terminal settling velocities of the particulates (droplets) as well as droplet trajectories and settling times.

Inertial impaction is another a physical phenomenon particles in motion experience during **turbulent flow**; turbulence or turbulent flow is fluid motion characterized by chaotic changes in pressure and flow velocity. It is a process in which particles are removed from a gas (air) stream by forcing the gases to make sharp directional changes or impinge on collection surfaces. For bio-aerosols originating from breathing, speaking, coughing, sneezing, etc., coughing and sneezing are generally turbulent events.

Convection is the name given to the movement of gases or liquids. When applied to aerosols, it is the movement caused by warmer and thus less dense gases to rise while colder, denser materials sink; this is a natural process which creates wind. F**orced convection** is the movement of gases (and liquids) caused by external forces such as wind, fans, pumps, compressors, etc.

Filters (or masks) are often used to collect bio-aerosols because of their simplicity and low cost. When used in medical or scientific applications, these filters are generally described using the terms *pore size* or *equivalent pore diameter*; the filter pore size does NOT indicate the minimum particle size which will be collected by the filter; in fact, aerosol filters generally will collect particles much smaller than the nominal pore size. Based on articles published in the news media during the recently, it is apparent that many journalists are are not aware of the fact the number of 10 nm sized virus particles in the air (from respiratory functions) is very small, if not zero, and that viruses generally hitch a ride on larger liquid droplets which are collected by appropriately designed masks. It is this lack of understanding aerosol science which leads to the dissemination of much erroneous information.

HEPA (high-efficiency particulate air) filters have been the industrial standard for efficient filters since the early 1950s and must remove at least 99.97% of particles whose diameter is equal to 0.3 µm from the air that passes through. Agglomeration predominates below the 0.1 µm diameter particle size, while impaction and interception predominate above 0.4 µm. Larger particles are unable to avoid fibers by following the curving contours of the air stream and are forced to embed in one of them directly; this effect increases with diminishing fiber separation and higher air flow velocity. HEPA filters are critical in the prevention of the spread of airborne bacterial and viral organisms. Typically, medical use HEPA filtration systems also incorporate high-energy ultra-violet light units and/or panels with anti-microbial coating to kill any live bacteria and viruses trapped by the filter media. Some of the best-rated medical HEPA units have an efficiency rating of 99.995%, assuring a very high level of protection against airborne disease transmission [29]. It should be noted that collection efficiency standards for filters are listed as weight percent and are not based on particle count. Since larger particles predominate collected particle weight, meeting efficiency standards may nevertheless result in the emission of many small particles.

BIO-AEROSOL EMISSIONS FROM NORMAL HUMAN ACTIVITIES

The results of many studies performed during and following the the SARS-CoV-1 epidemic some 15 years ago as well the later MERS-CoV and other influenza episodes have shown a significant potential for inhalation exposure to viruses in microscopic respiratory droplets. These retrospective studies demonstrated that airborne transmission was the most likely mechanism, after ruling out infection from human to human or contaminated surface contacts. There is every reason to expect that SARS-CoV-2 (Covid-19) behaves similarly, and that transmission via airborne micro-droplets is an important infection pathway. Active viral particles associated with droplets smaller than 5 µm have been detected in air and the virus has been shown to maintain infectivity in droplets of this size [20].

The following sections review recent experimental data and modeling results published in various engineering, scientific and medical journals, addressing these important topics:

- Characterize droplets emitted during human activities
- Respiratory Droplet behavior: trajectories, settling and evaporation
- Effectiveness of masks (filters) in mitigating droplet emission
- Miscellaneous airborne viral hazards (singing, instruments, toilets, etc.)

AIRBORNE DROPLET EMISSIONS DURING HUMAN ACTIVITIES

Anyone who is observant has seen small droplets emitted from the mouth while interacting with family, friends or neighbors. Scientists have studied these aerosols for many decades; a recent study of particles emitted during coughing and sneezing cited the data shown below from a 1946 study:

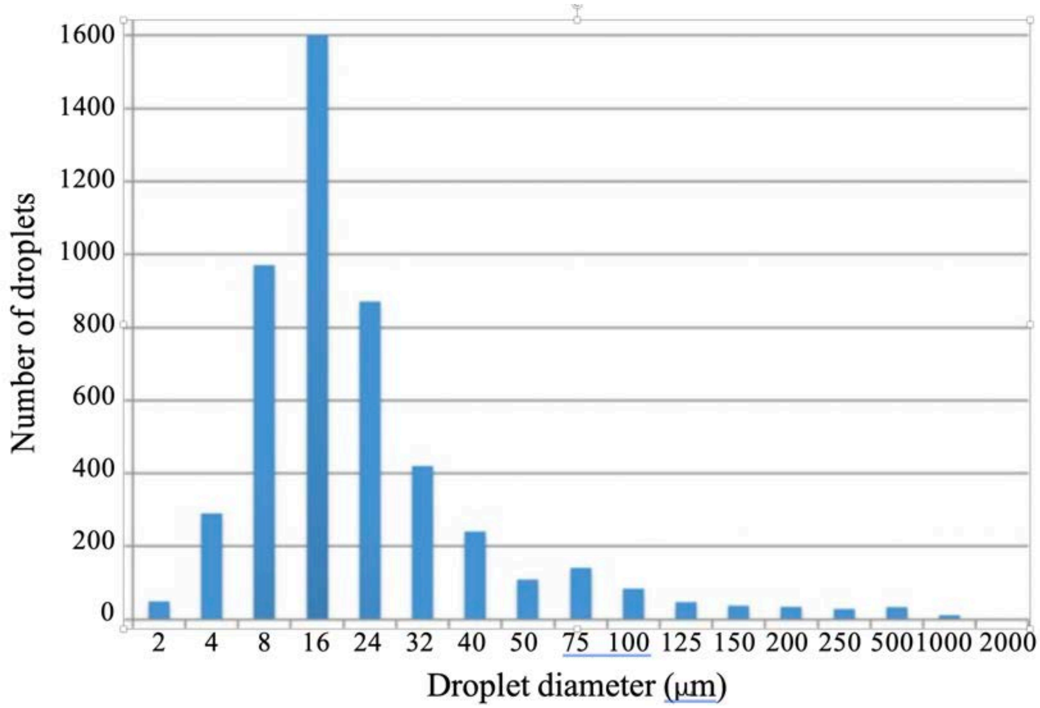
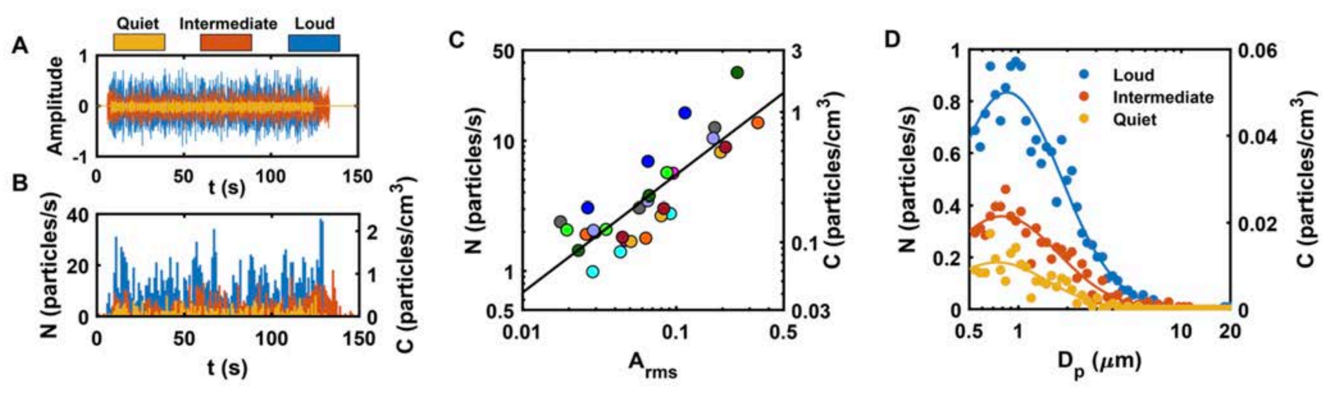


Figure 1: Histogram of droplet sizes in coughs [9, citing Duguid, 1946]

Considering that the data shown in Figure 1 was generated over 70 years ago when instrumentation was rather rudimentary, it is remarkable that it shows the expected bell-shaped particle size distribution centered around a particle size of 16 µm. A study performed in 2016 explored the variation in droplet emissions for human speech at different loudness levels [1]; Figure 2-D below shows that modern instrumentation shifts the apex of the droplet size distributions to ~1 µm with the number of particles emitted at an intermediate voice level about double those emitted at the quiet level and doubling again at a loud level. While the concentration of particles emitted appears to be low, the units are in particles per cubic centimeter and must be multiplied by ~16 or ~28,000 to convert to cubic inches or cubic feet, respectively.



A. Superimposed representative recordings of amplitude (arb. units) for an individual reading the passage at three different voice amplitudes.

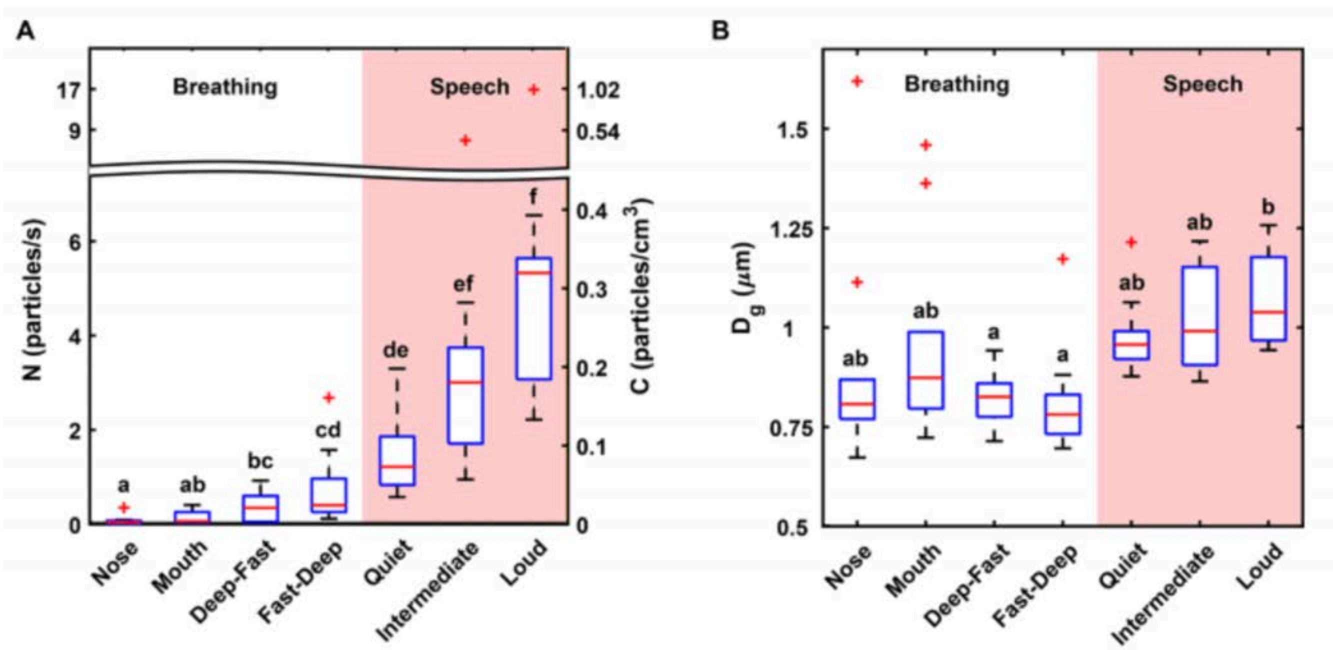
B. The corresponding number/concentration of particles measured by the APS versus time.

C. Particle emission rate/concentration as a function of root mean square amplitude, A_{rms}, for 10 participants, 3 points for each person, representing 3 voice amplitudes.

D. Representative particle size distribution for the one individual.

Figure 2: Particle emission rate/concentration while reading at three different loudness levels [1]

Figure 3 below presents additional data comparing the emission rate/concentration and corresponding mean diameters of particles emitted during various breathing modes with those during speech at different loudness levels, with the speech data corresponding to that shown in Figure 2 [1].



Emission rate/concentration **Corresponding geometric mean diameters**

Red lines indicate medians, while blue boxes indicate the 25th and 75th percentiles respectively; sample size is 10. Outliers (defined as values that exceed 2.7 standard deviations) are indicated with red plus signs.

Figure 3: Comparison of emission rate/concentration with the corresponding mean diameters of particles emitted during various modes of breathing versus speech at different loudness levels [1]

Data presented in Figure 3 is consistent with Figure 2 and adds emissions during normal breathing. It is interesting to note that droplet diameters tend to increase somewhat during speaking.

It should be noted that droplet size distributions listed in the literature can vary considerably; several recent investigators have cited the same 2009 data for saliva droplet sizes shown in Figure 4. Here the droplet size distribution centers around 70 µm, significantly greater than data shown in Figures 1-3 above.

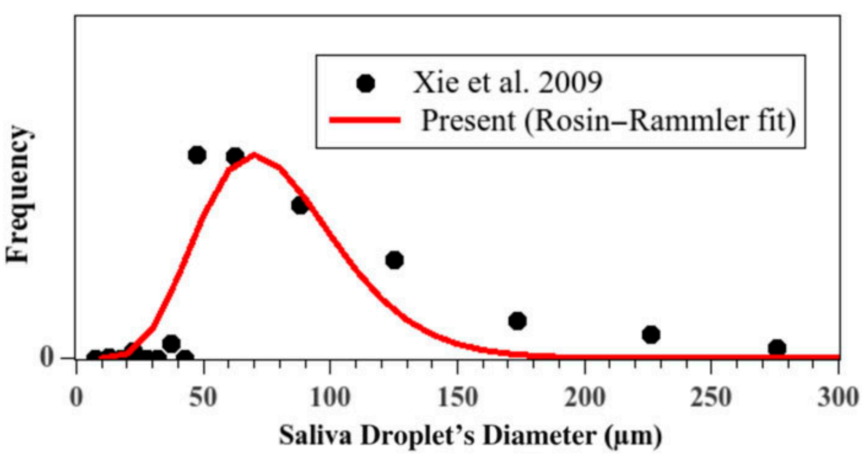
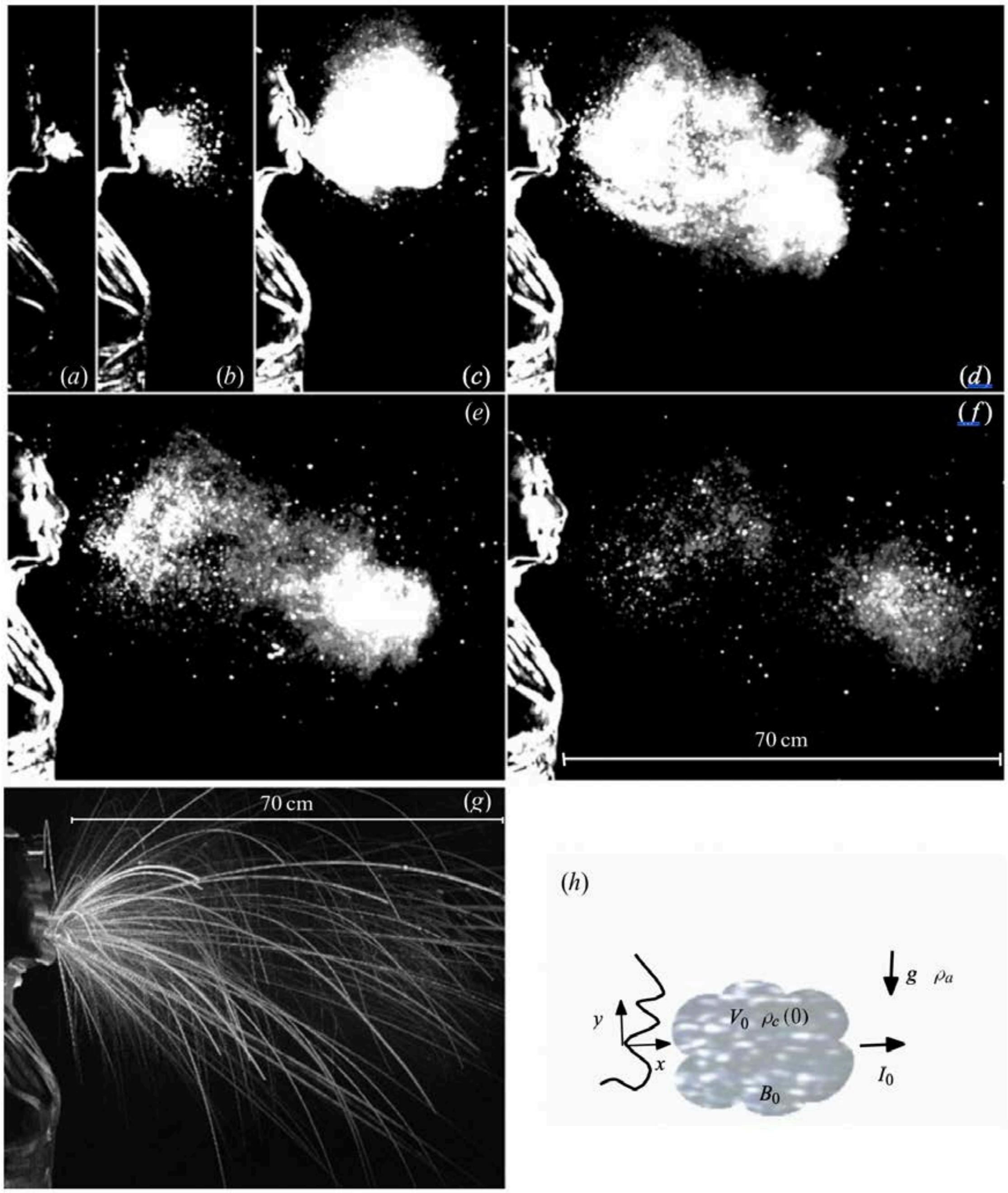


Figure 4: Initial saliva droplet size distribution [13]

During the last decade a number of investigators have studied the extent of droplet emissions during coughing and sneezing [8,9,10,13,14,23,25,26]. The following three high speed photo sequences in Figures 5, 6, and 7 illustrate the fact the droplets ejected during either event can travel over 20 feet, significantly further than the CDC recommended six feet for social distancing.



(a) 0.006 s, (b) 0.029 s, (c) 0.106 s, (d) 0.161 s, (e) 0.222 s and (f) 0.341 s.
(g) Trajectories of the largest droplets are revealed through a streak image
(h) A schematic of the initial cloud with characteristic initial momentum I_0, buoyancy B_0 and volume V_0 emitted into quiescent ambient air.

Figure 5: High-speed images of a sneeze recorded at 1000 fps [9]

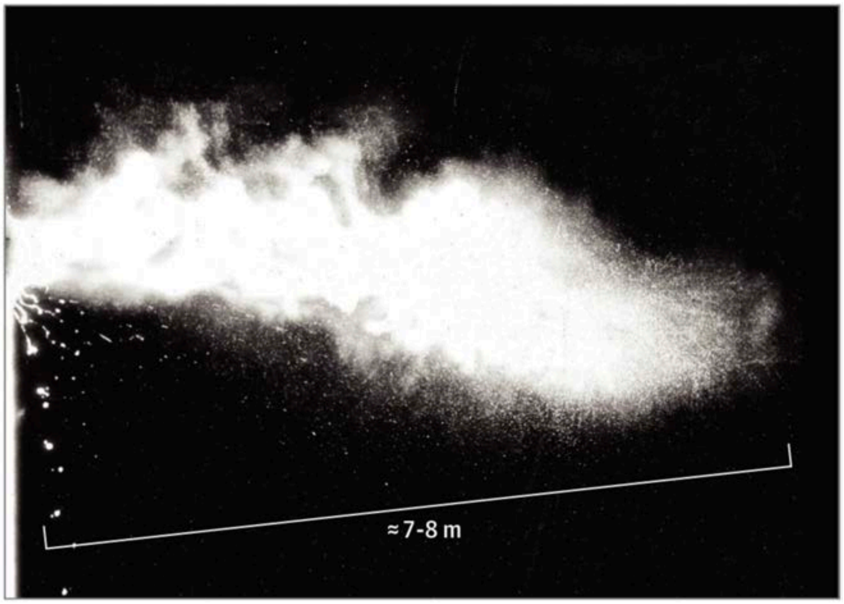
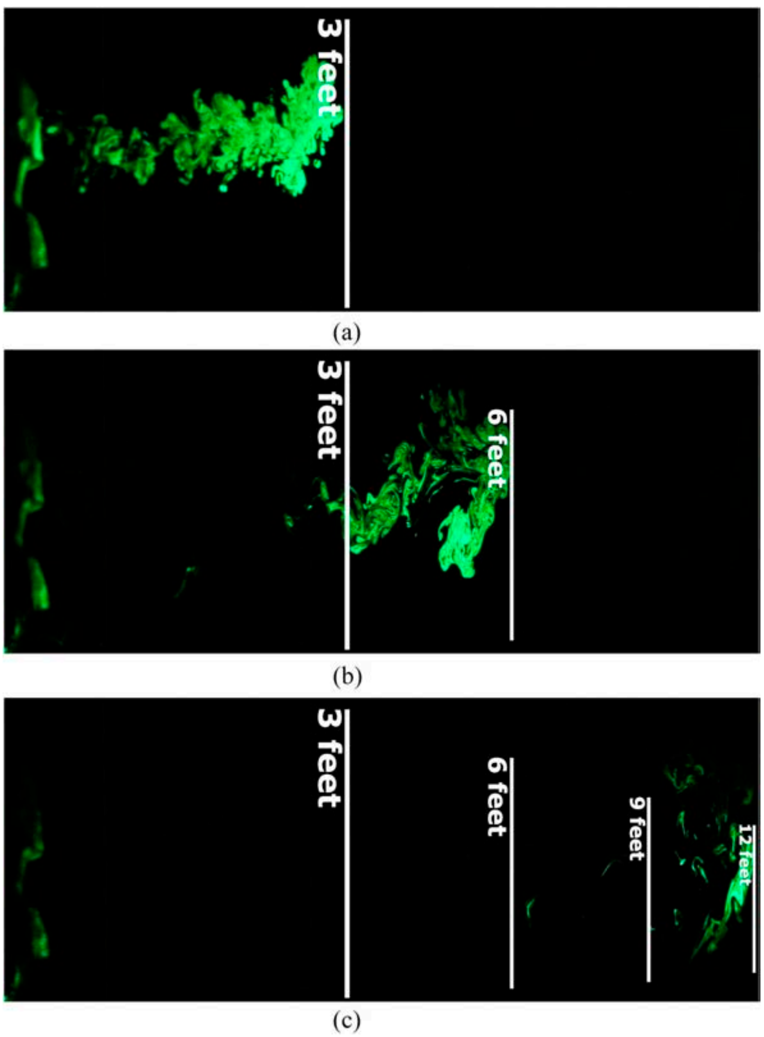


Figure 6: Multiphase turbulent gas cloud from a human sneeze [8]



Images taken at (a) 2.3 s, (b) 11 s, and (c) 53 s after the initiation of the emulated cough.

Figure 7: An emulated heavy cough jet travels up to 12 ft in ~50 s [26]

AIRBORNE RESPIRATORY DROPLET BEHAVIOR

With the data presented above, the behavior of emitted droplets under ideal conditions can be anticipated. Unfortunately, the ideal conditions seldom exist: indoors, we experience air currents due to heating/cooling equipment, fans or open windows; outdoors, varying air currents may disperse any droplets while they decrease in size due to evaporation or become larger due to agglomeration or condensation. Again, considerable experimental and modeling work has been published in the last decade, providing a good scientific understanding of this complex, dynamic system.

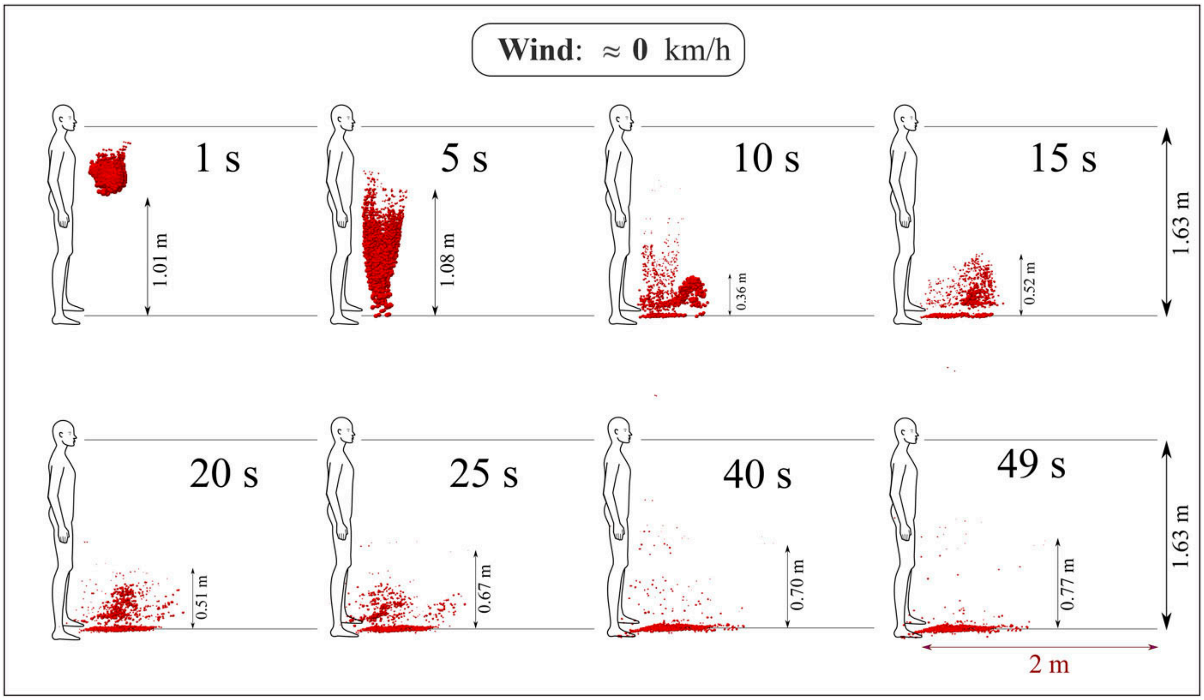


Figure 8: A human cough: saliva droplet's disease-carrier particles cannot travel more than 6.5 ft in space at zero wind speed. Temperature, pressure, and relative humidity are 20 °C, 1 atm, and 50%, respectively [13]

While using the droplet size distribution from Figure 4, Figure 8 projects that most droplets will start settling within the initial 5 seconds, will be mostly settled by 50 seconds and will not travel much beyond 3 feet. We do need to note, however, that the droplet size distribution used in this study has a mass median diameter of about 70 µm. A droplet distribution such as the one shown in Figure 2-D, a mass median diameter of about 1 µm, will not settle this quickly.

When convective currents are introduced, i.e. wind, droplet settling times increase dramatically. Figure 9 below shows that with a 2.5 mph (4 km/h) cross wind, droplets will disperse and settle somewhat, but will be mostly airborne below the line of sight at 20 feet. With a 9.5 mph (15 km/h) crosswind, dispersal increases, settling decreases while many of the droplets are still at or above the line of sight at a distance of 20 feet. If we are to assume that the droplet size distribution is closer to Figures 1 or 2, there will be very little settling of any droplets in Figure 9.

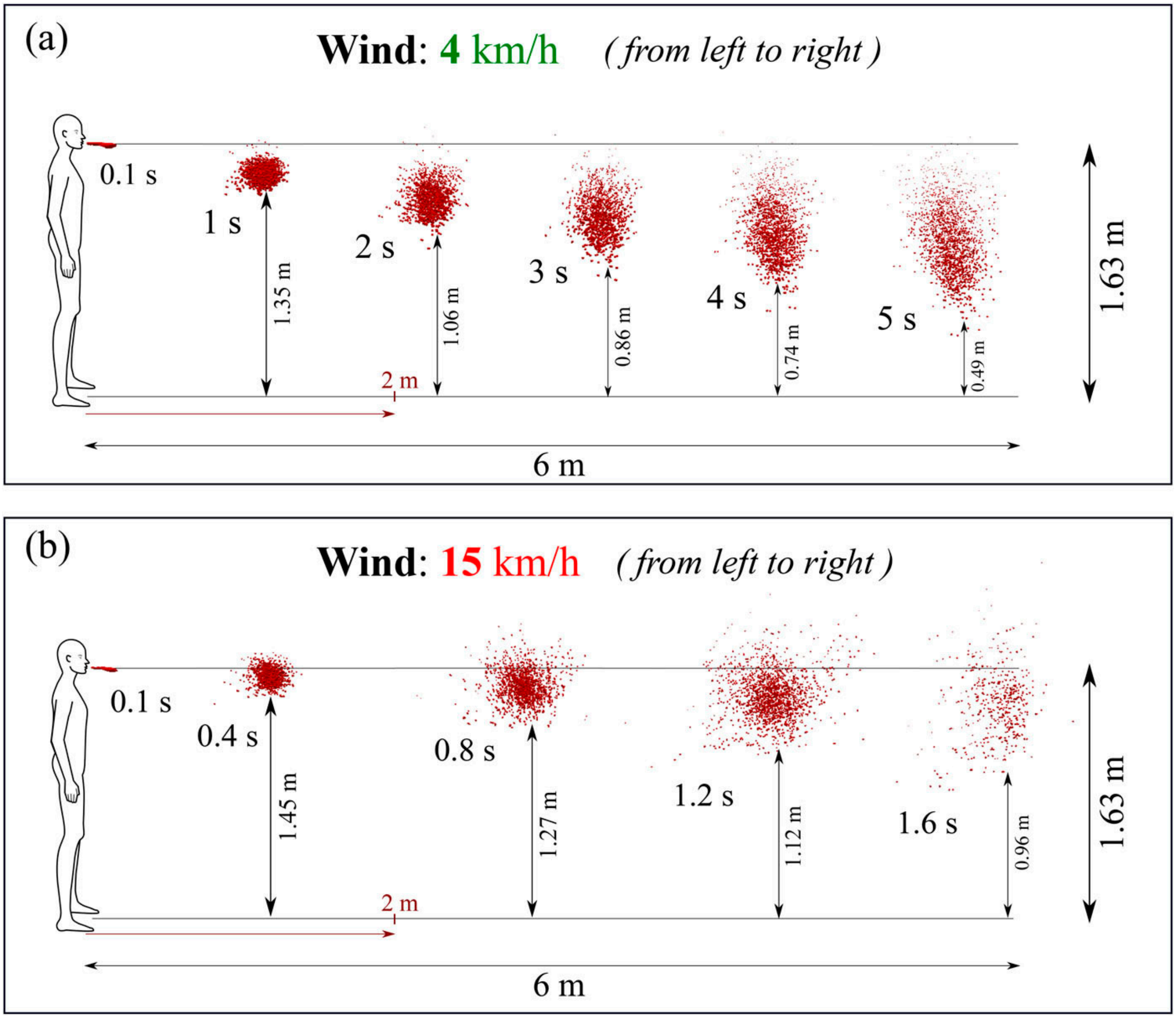


Figure 9: A human cough: saliva droplets may travel in the air medium to considerable distances depending on the environmental conditions. This figure shows the effect of wind speed on the saliva droplet and transport under dispersion and evaporation. Wind blowing from left to right at speeds of 4 km/h (a) and 15 km/h (b). Temperature, pressure, and relative humidity of 20 °C, 1 atm, and 50%, respectively, with the ground temperature at 15 °C [13]

Results of the computational model resulting in Figures 8 and 9 include evaporation of some of the liquid in the droplets. Figure 10 backs out the effect of evaporation and shows that in the absence of convection (no wind) droplet mass may be reduced by up to 70% during the initial 10 seconds and up to 90% in the presence of wind at 2.5 mph. Reference 13 represents an interesting study using rather sophisticated computational fluid dynamics along with substantial computing power to solve the resulting sets of equations for each represented particle size; in order to simplify the mathematics and make the system solvable, it appears to have approximated saliva droplets with water. Another recent investigation into respiratory droplet physics [12] considered only the fate of droplets over time using a first principle approach and approximating droplet with saline solution, i.e. containing salt. The study compares the fate of water droplets with those of droplets containing 1% salt (NaCl) and presents modeling as well as experimental verification of the models; Figure 11 presents the results.

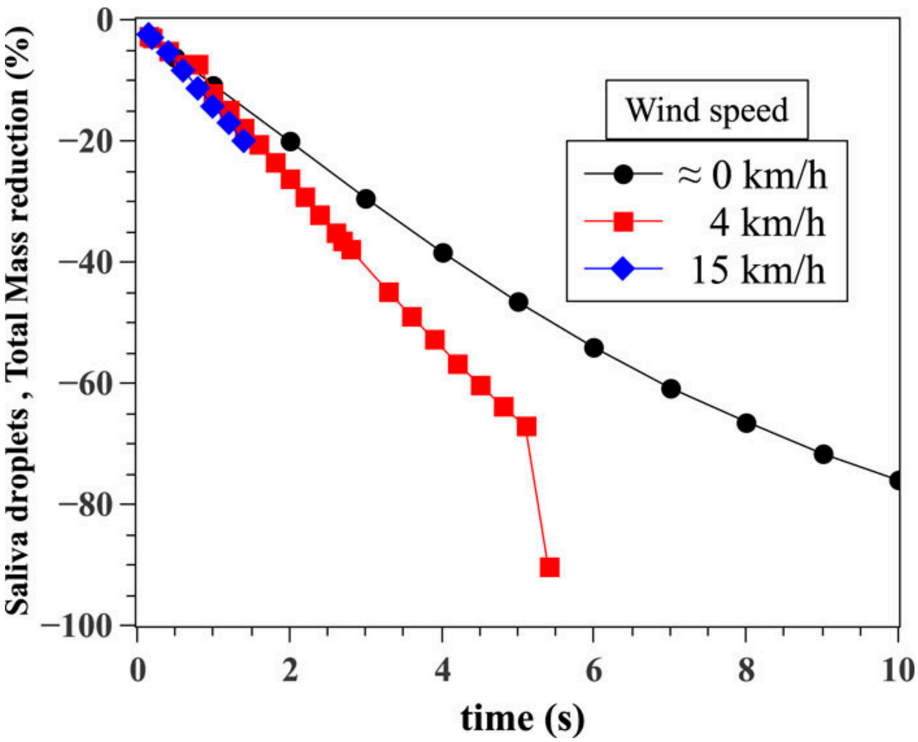


Figure 10: Saliva droplet mass reduction over time compared to the initial mass [13]

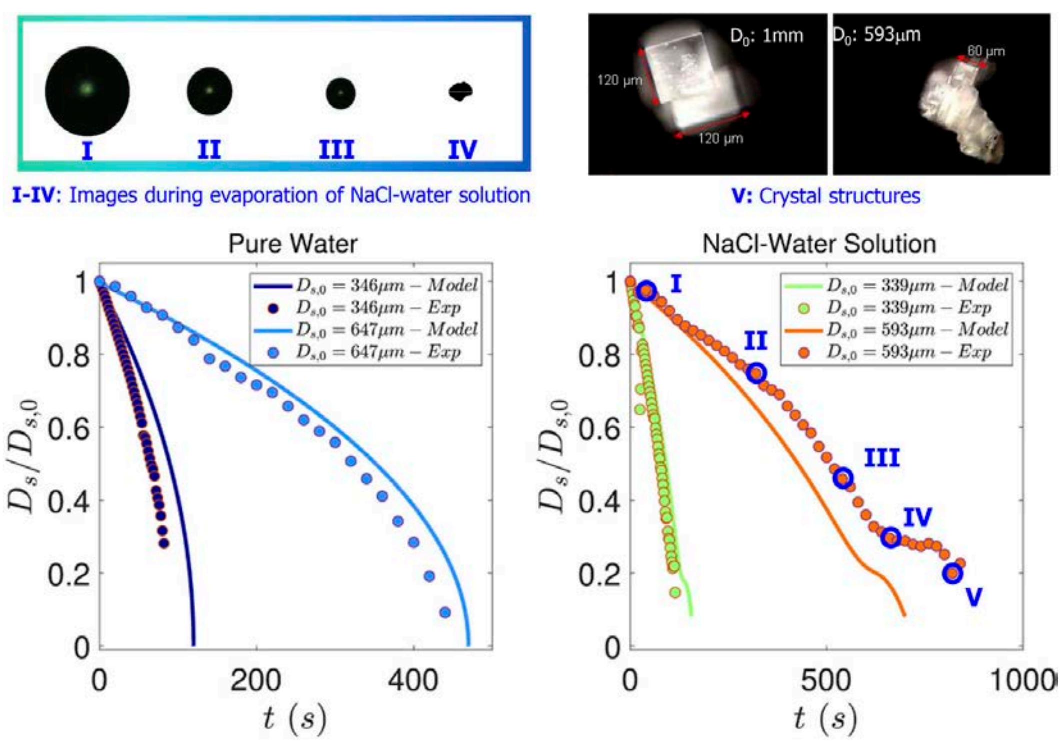


Figure 11: Evolution of the normalized droplet diameter as a function of time for pure water and the salt water solution droplet with 1% NaCl [12]

Comparing Figure 11 data with Figure 10 presents some interesting differences: the time axis in Figure 10 is only 10 seconds while Figure 11 extends to 400 seconds for the water data and ~800 seconds for the water-salt system. As droplets evaporate, the salt-containing particles reach a steady state size at about 70% weight loss at ~600 seconds, due to the salt concentration near their surface retarding further evaporation. The final state of the salt droplet appears as salt crystals (probably with water and air inclusions) at about 20% of the original mass at ~800 seconds. The y-axis (left scale) of the graphs in Figure 11 represents a normalized ratio of the droplet diameters, i.e. the actual current diameter divided by the original starting diameter.

Recognizing that the survival rate of respiratory droplets depends on ambient conditions, including the relative humidity, an additional recent modeling approach included regional average humidities as a variable input and concluded that humid locations such as New York and Chicago may have droplet survival times almost three times longer than low humidity cities like Los Angeles [5].

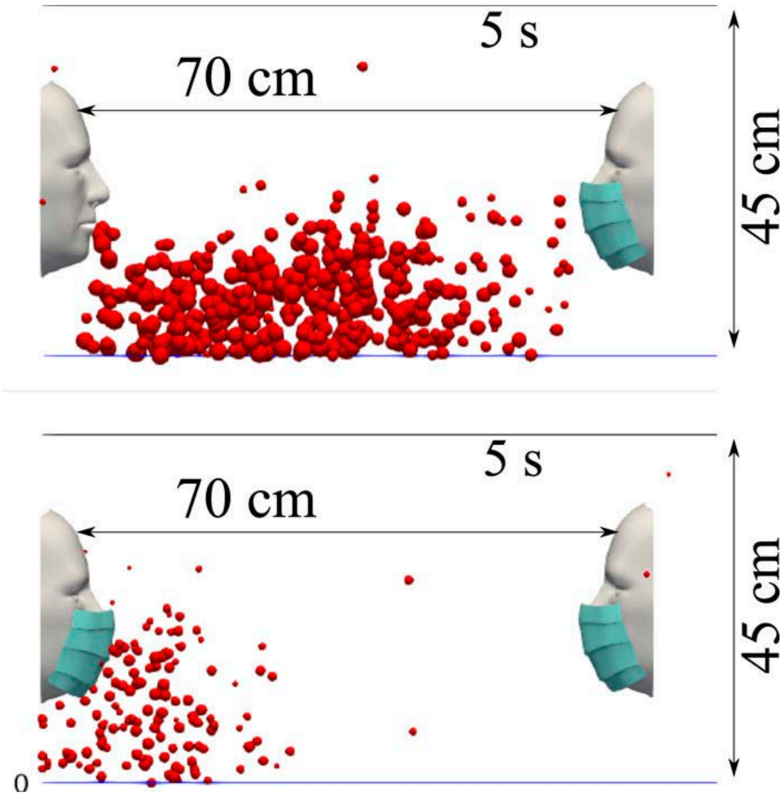
Effectiveness of Masks (Filters) in Mitigating Respiratory Droplet Emissions

During the last several months, much misinformation or disinformation on masks has been discussed, shared over social media and published by the press. Even current CDC guidance on masks is incomplete in that it encourages the use of masks, provides instructions of how to make simple masks, but provides no guidance whatsoever as to what constitutes a good mask with reasonable collection efficiencies. The guidance states that we need to reserve available surgical and N95 masks for medical personnel and first responders and provides instructions on how to make masks from ordinary (cotton) handkerchiefs; as we will show below, ordinary cotton is about the worst material for masks, providing very little protection to the wearer and the bystanders.

An interesting story about developing efficient masks showed up the news media in early April 2020 [7]: a small clothing manufacturer wanted to keep their employees working and decided to start making masks. When investigating collection efficiencies of various textiles, they discovered that available masks were exhibiting low overall collection efficiency and that the use of bandanas recommended by the CDC, was worse. Ultimately, they started a research project, purchased a commercial particulate counter and investigated different textiles for filter materials, arriving at polypropylene (microfiber) cleaning towels and blue shop towels both of which have collection efficiencies above 90%. It is interesting to note that a small boutique clothing manufacturer can arrive at these impressive results while a multi-billion dollar government agency provides advice which is potentially dangerous to the user and the community.

An earlier academic study of the efficacy of using homemade masks for influenza virus protection was published in 2013 [27]; it considered a variety of different fabrics along with surgical masks and vacuum cleaner bags, determining collection efficiencies and pressure drops across the systems. For most fabrics, collection efficiencies fell below 60%, reaching 70% for multi-layered cotton. By comparison, surgical masks reached 96% and vacuum cleaner bags 94%, while the later showed pressure drops double those of most fabrics. Pressure drops across mask textiles must be minimized in order to maximize wearer comfort.

Scientists have studied respiratory droplet collection efficiencies from various perspectives [4,14,26]. Figure 12 shows the effect of wearing a surgical mask on droplets emitted during coughing: subjects wearing a mask do reduce the respiratory droplet transmission while (partially) shielding themselves from other subjects experiencing a coughing incident [14]. Figure 13 illustrates the results of multiple coughing events on droplet capture; as droplets are initially captured by the mask, subsequent coughs will result in partial evaporation of those captured particles and an increase the emission of vapors (which is shown on the y-axis). While the initial filter capture efficiency is ~91%, subsequent coughs and the resulting droplet evaporation reduces overall efficiency as shown in Figure 14.



5 s simulation time for a surgical mask exhibiting an initial efficiency of ~91%.

Figure 12: Mask wearer: subjects wearing a mask will reduce the respiratory droplet transmission [14]

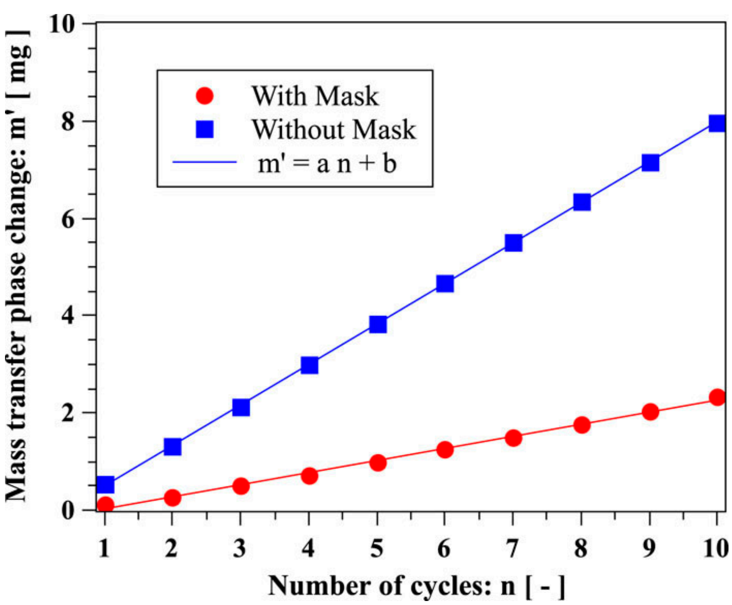


Figure 13: Mass transfer due to evaporation of respiratory droplets over ten cough cycles [14]

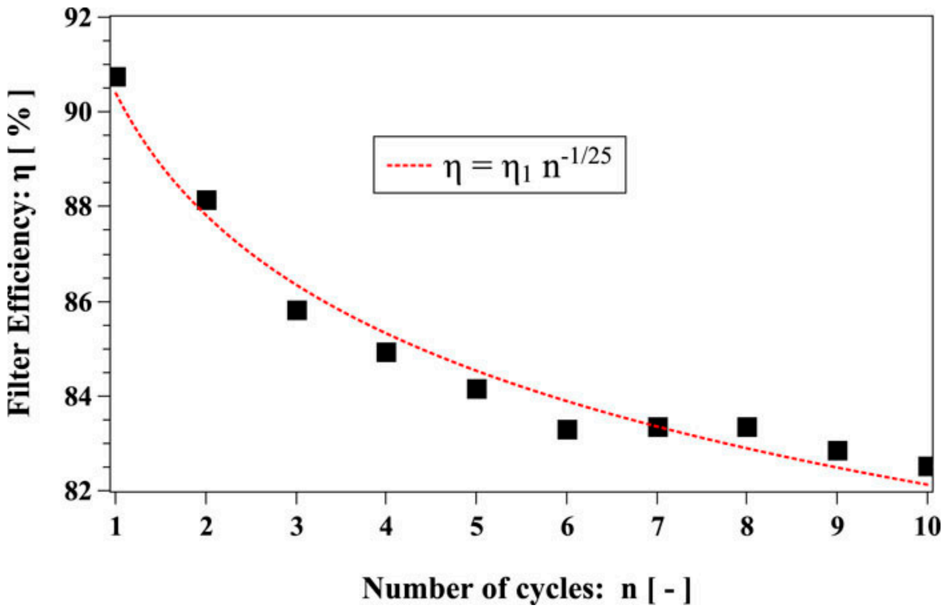
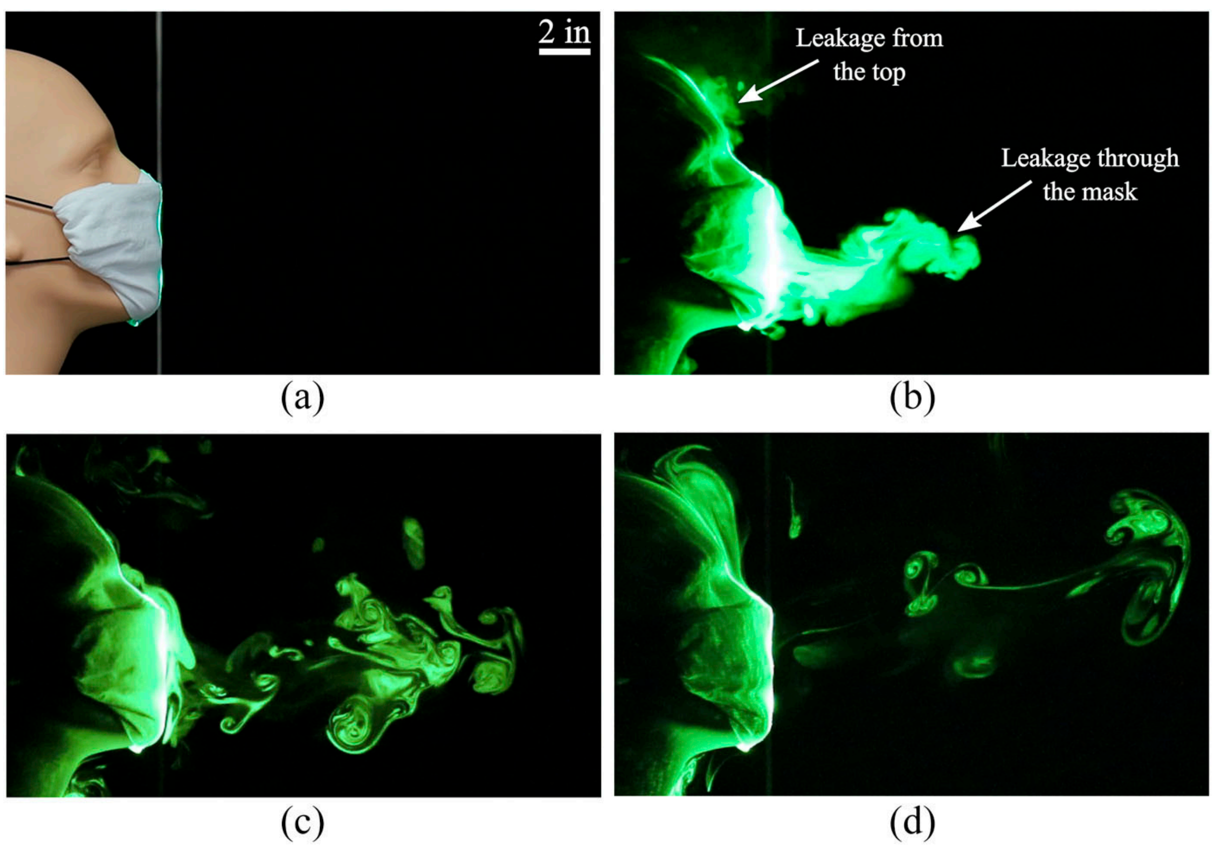


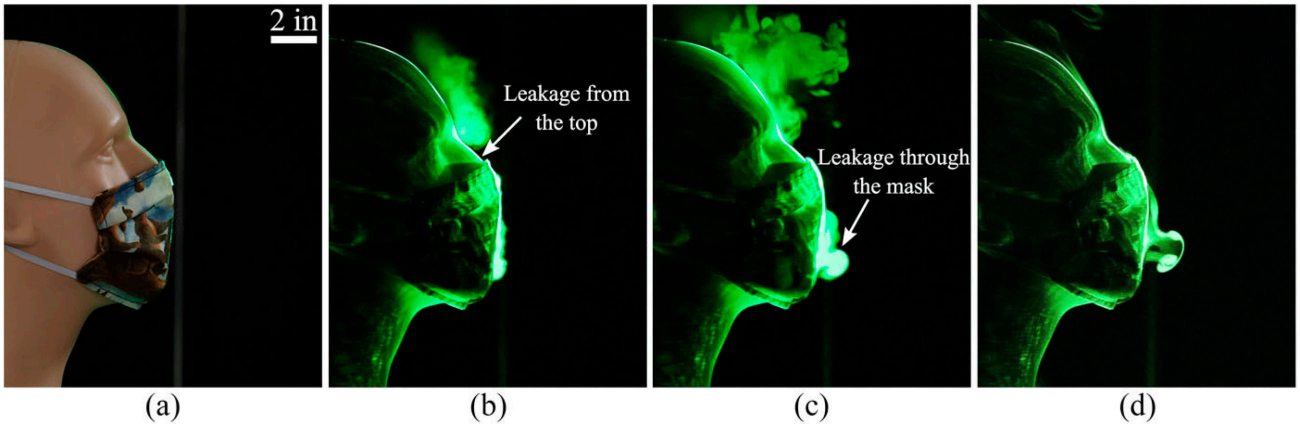
Figure 14: Filter efficiency over ten cough cycles [14]

Figure 7 showed photos of a cough traveling up to 12 feet. The same study provides visual clues to the capture efficiency of three types of masks: a folded handkerchief, a homemade 2-layer cotton mask and a commercial cone-shaped mask made of randomly oriented fibers, presented in Figures 15, 16 and 17 [26]. The mask depicted in Figure 15 approximates the example shown on CDC's web site.



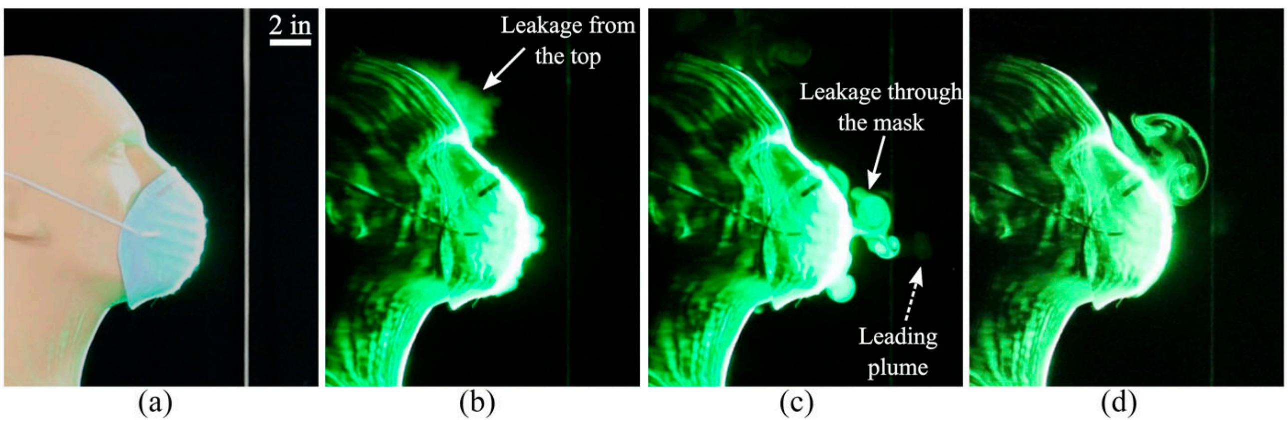
Images taken at (b) 0.5 s, (c) 2.27 s, and (d) 5.55 s after the initiation of the emulated cough

Figure 15: A face mask constructed using a folded handkerchief [26]



Images taken at (b) 0.2 s, (c) 0.47 s, and (d) 1.68 s after the initiation of the emulated cough.

Figure 16: A homemade face mask stitched using two-layers of cotton quilting fabric [26]



Images taken at (b) 0.2 s, (c) 0.9 s, and (d) 3.7 s after the initiation of the emulated cough.

Figure 17: An off-the-shelf cone style mask [26]

These series of emissions images from 3 types of masks clearly show that the choice of textile used and the design of the mask are important in protecting the wearer as well as bystanders. Along with earlier data on surgical masks, it should be obvious that a good design must minimize leakage through the mask as well as along the top and sides. Mask efficacy depends on the ability of the mask to trap or alter the high-momentum gas cloud emission with its droplet payload; peak exhalation speeds can reach up to 33 to 100 feet per second, creating a cloud that can span approximately 23 to 27 feet [8]. A recent article on shortcomings of current masks along with a list of possible improvements stressed that air leaks along the top need eliminating, stretchable fabrics and low pressure drop increase comfort and a need to consider aesthetic matters [15].

Many of the currently available masks have one major design problem: they contain a breathing valve which will facilitate exhaling and decrease pressure drops across the mask. However, while the mask wearer is protected others in the vicinity are not. While many facilities now require visitors to wear masks, most will accept masks with breathing valves, including medical establishments. Masks with exhaust valves are great when used in high dust locations, but have no use in controlling infectious diseases.

One method of increasing the effectiveness of any mask is the use of an additional filter insert; PM 2.5 inserts are readily available. The insert is placed via a slit between the fabric layers of the mask; it is discarded when the mask is washed. The use of a filter insert with a home made mask of a combination of layers of microfiber cloth and shop towel will result in a high efficiency mask at low cost. Mask patterns are available online from many organizations, including the CDC.

One interesting online database with current information on an extensive list of fabric/textile testing for masks, including data on pressure drops, may be found at smartairfilters.com [24]. While some of the data available on the site may not match that of refereed publications concisely, it should be noted that experimental data may exhibit variability when studying these type of multi-variable, complex systems where condensation or evaporation may be occurring. The web site reference provided below will lead to a section of the site which provides 3 URLs for assisting DIY efforts in mask making.

One last item related to mask use is a discussion of potential adverse health effects when wearing a mask. Conspiracy theories on negative health effects of masks have proliferated ever since the current pandemic began. There is no scientific or medical information substantiating these theories. One claim has been that wearing a mask will continue to reinfect the wearer; once someone is infected, a mask will protect everyone around but have no other effect on the wearer. Another often heard complaint is that wearing a mask will lower the wearer's body oxygen level; this is another topic which has been investigated extensively with results showing that masks have no effect on the body oxygen concentration. One last claim to address is the notion that mask wearing will increase body carbon dioxide concentration; this claim is somewhat correct. Extensive masks may increase body carbon dioxide concentration marginally, however, experimental data shows that any resulting small increases will still be significantly below allowable concentrations. In fact a good comparison to the last 2 claims is data derived from residential air quality assessments: many individuals are confined for long periods in closed rooms without fresh air ingress; data for these situations show that oxygen levels generally stay level over 8 hours while carbon dioxide may increase from 0.1% to 0.3%, significantly below the OSHA 8-hour exposure recommendation. Finally, other potential mask problems that have been addressed in past studies indicate that mask wearing has no discernible effect on blood pressure or heart rate of the wearer. Smartairfilters [24] addresses these issues on their site.

Miscellaneous Airborne Viral Hazards

Music Programs

With choirs at many churches, schools and colleges, as well as orchestral and band programs, the question has been posed if these programs are a health risk in the current pandemic. An excellent review of potential problems and ongoing research has been assembled by a choir director on her private web site, providing links to many of the ongoing international studies [22]. While there are many claims by various authors that singing is perfectly safe, the reality is quite different. Towards the end of May 2020, NPR reported that the CDC had posted the following warning [11]:

> "Consider suspending or at least decreasing use of a choir/musical ensembles and congregant singing, chanting, or reciting during services or other programming, if appropriate within the faith tradition. The act of singing may contribute to transmission of COVID-19, possibly through emission of aerosols."

Earlier, the CDC had investigated a choir practice incident. One person out of the 61 people who attended the practice was known to be symptomatic; 53 cases of coronavirus infection were later identified. In spite of the available real data, under White House pressure the CDC removed the above notice a few days later from its web site.

In order to generate current data on possible health effects of music programs, the National Federation of State High School Associations (NFHS.org) has sponsored an international coalition to study music programs. The group has issued an initial preliminary report covering droplet emissions from voice and wind instruments [28] and plans periodic updates as additional data is generated. The results to date indicate that singing and wind instruments generate significant respiratory droplets; detailed data on voice and individual instruments is available in the referenced report.

Public Toilets

Public health experts, designers and architects believe that the Covid-19 pandemic has exposed fundamental flaws in the design of public toilets, increasing the risk spreading the coronavirus via the many potentially virus carrying surfaces found in all typical facilities. One reason for including a discussion of public toilets as a potential source of airborne infectious particles is the fact that the mere flushing of a toilet may release a significant column of droplets, known as the toilet plume. While the COVID-19 virus has been found in the feces of infected patients, until recently there was no data on whether such viral remnants are biologically viable or sufficient to infect additional persons. However, the CDC just published a study indicating that active viral remnants may be present in feces [30]. It is interesting to note that many municipalities are now trying to assess the degree of infection in their communities via waste water analysis.

A recent publication has presented a detailed computational fluid dynamic model of the toilet plume [18] for two types of toilets generally encountered, the single inlet unit normally found in public restrooms and the annular (rim) flush toilet found mostly in residential use. Figures 18 and 19 show the predictions for aerosol droplet emissions at 35 and 70 seconds following a flush and indicate strong turbulence in both types of toilets with an upward droplet velocity as high as 15 ft/s, emission of between 1500 - 2700 droplets per flush, and up to 60% of all droplets rising above the toilet seat. At 70 seconds aerosol plumes are predicted to be ~32 inches above floor level for single inlet and ~42 inches for annular inlet toilets.

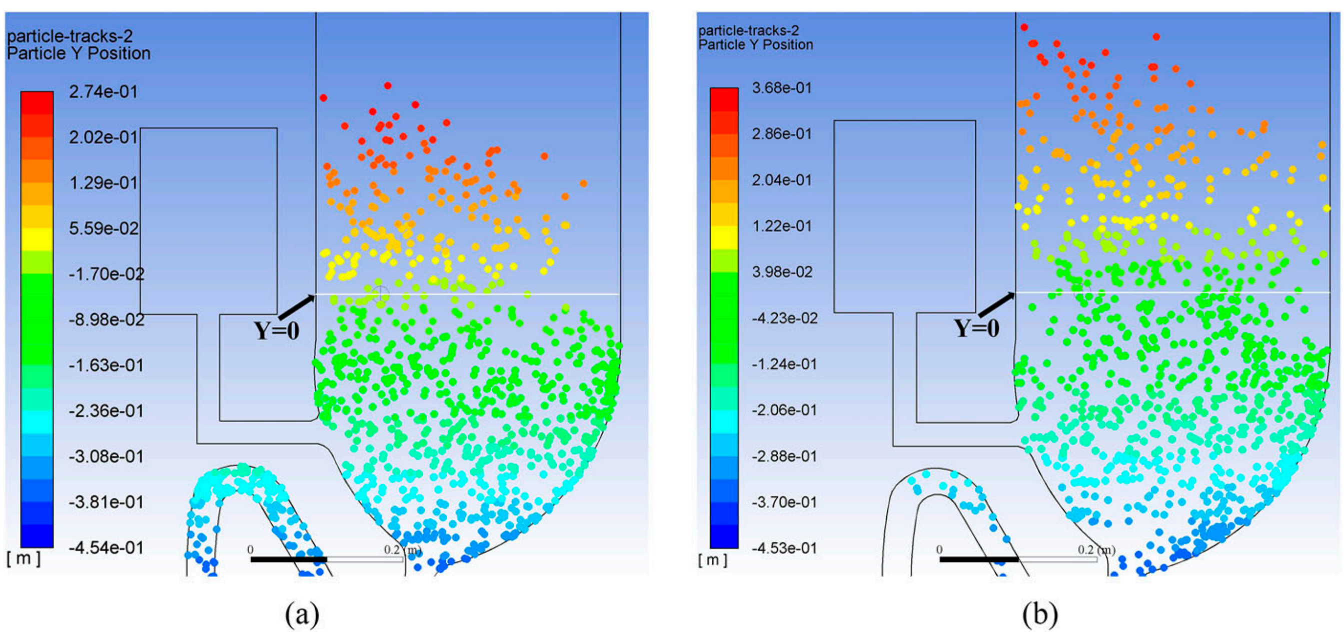


Figure 18: Aerosol distribution for single-inlet flushing at a time of (a) 35 s and (b) 70 s [18]

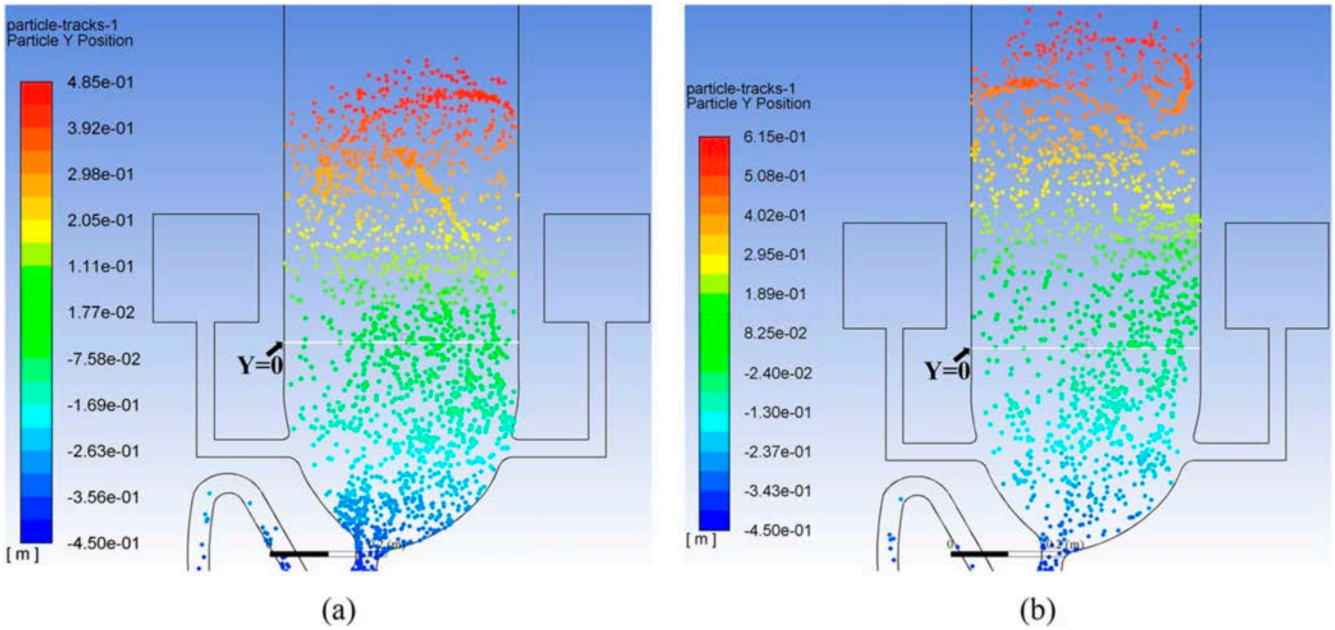


Figure 19: Aerosol distribution for annular flushing at a time of (a) 35 s and (b) 70 s [18]

The obvious immediate solution for minimizing exposure to a toilet plume is to put the lid down prior to flushing, something that is difficult to do in public restrooms which normally do not have lids. Based on the above data, it is safe to assume that all surfaces inside the the toilet stall, such as the lid and paper dispenser, are contaminated along with the many other potential virus carrying surfaces found in all typical facilities.

Conclusions & Recommendations

Normal human activities will result in the emission of respiratory droplets which may become carriers for airborne pathogens. Other activities such as yelling, singing, playing wind instruments, coughing and sneezing will increase the ejection of respiratory droplets as well the distances traveled by them.

While CDC guidance on social distancing has remained at 6 feet and many news commentators have suggested to bring the indoors outdoors, this guidance must be accepted with a great deal of skepticism. Scientific experimental data and associated modeling efforts have clearly demonstrated that without masks, outdoor distancing should be at least 20 feet.

Guidance for indoor gatherings recommends a well-ventilated room. Unfortunately, the principles of forced convection apply equally indoors and outdoors. Unless the indoor space is protected by a properly designed and well-maintained HEPA filter system, moving air with fans or normal air handlers will only extend droplet settling times as shown in Figures 8 and 9 and enhance droplet dispersion; opening windows to allow outside air to enter a room may dilute any airborne pathogens, as long as they are not reintroduced through air HAVC equipment, but will not eliminate them.

Wearing a face mask protects the wearer from the surroundings as well as others in the vicinity from the wearer. Although masks will reduce droplet transmission, some droplets will be transmitted away from or through the mask. The use of a mask will not prevent airborne droplet transmission completely.

It should be noted again, that mask capture efficiency data provided in the various cited references is always stated as weight percent capture. Inefficient cotton cloth masks may exhibit efficiencies between 20% - 60%; even at a 60% capture rate, these masks will pass in excess of 95% of the number of smaller particles exhaled, leading to a false sense of security for the wearer.

Mask efficiency is dynamic and changes with the length of time the mask is worn. When collected droplets evaporate and the vapors are passed through the mask, it is possible that pathogens on the droplet surface will adhere to the vapor passing through the mask.

Available experimental data show that wearing a face mask has no detrimental effects on the wearer, body oxygen level does not change, while carbon dioxide levels may increase slightly, but not beyond what is normally encountered in a closed room; there is no effect on heart rate or blood pressure.

It has been demonstrated that aerosols are released as part of flushing toilets and it is known feces may contain pathogens, including remnants of Covid-19. The most recent data suggests that such viral remnants may be biologically viable and sufficient to infect additional persons.

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