UNDERSTANDING PARTICLE SIZE & AEROSOL-BASED TRANSMISSION

ABOUT THE AUTHOR

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INTRODUCTION

On July 04, 2020 the NYTimes published an article stating a claim by WHO "we have been stating several times that we consider airborne transmission as possible but certainly not supported by solid or even clear evidence," This paper documents the math and science with exact calculations detailing aerosol-based transmission and deposition in the lungs. In addition, the paper clarifies the misuse of terms like "airborne", "droplet" and aerosol and the misapplication of these terms to "six feet" of social distancing.

The misuse of these terms is leading to the senseless deaths of hundreds of thousands of individuals. Each particle size has different risk reduction measures as documented in Section 2 of the paper. The application of the "six feet" guidance has zero benefit for particles containing the corona virus with the greatest deposition rates in the alveoli of the lungs. (particles ranging from 0.068 micron to 7.0 microns).

A particle's size is the main characteristic determining the transport properties. Large particles are governed by Newton's law. Small particles are governed by Stokes' law. Very small particles are governed by diffusion. The Reynolds number for a particle determines if Newton's law or Stokes law is the governing equation. When size is very small, Stokes' Law requires a correction factor, Cunningham slip, to account for particles slipping between molecules of air. At the smallest end of the spectrum we see very high slip conditions and diffusion behavior from aerosol particles. These are important concepts when it comes to the coronavirus and particles.

While all these particles are airborne, those governed by newtons law are called droplets in the media; those particles governed by Stokes' law are referred to as aerosols. The distinction between "airborne" particles, "droplets" and "aerosols" has caused much confusion. What really matters?

The particles of greatest concern generated from a human are particles between 0.068 and 7 micron(s) governed by Stokes' law with a Cunningham slip.

The particles deposited in the alveoli in the lungs are of the most concern. The particles which travel the deepest into the lungs are particles governed by Cunningham slip and Knudsen's number. A portion of these particles will deposit on the walls of the upper respiratory tract. Particles between 0.068 micron and up to 7 microns have the highest deposition rate in the alveolar region of the lungs. A corona virus or clump of corona viruses have particle sizes in this range. Thus we would expect high deposition rates based on the math and science of particle behavior as documented in this paper.

How long will a coronavirus laden particle stay entrained in the air? The settling velocity for various sized particles is calculated in Appendix A. The settling velocity for a particle with the diameter of one coronavirus is 1 meter per 87.4 million seconds. This means in the absence of any air flow the particle would take 48,555 hours to settle to the ground for a 2-meter tall person and half that for a 1-meter tall person. The air flow in a room is always higher than the settling velocity of a corona virus particle. What this means in real terms is that these particles move with the air flow pathway in the room.

How many people can one symptomatic person infect? Are there super-spreading people or super-spreading conditions?

One person may infect up to 216 people based on particle generation rates and aerosol transmission.

"Adult humans inhale over 10,000 liters of air per day. Contained within this air are somewhere between 100 billion and 10 trillion particles." (Tsuda et al., 2013)

Around 5,000 particles are generated per breath, more for singing, exercise, etc. The average number of breaths per 8-hour period is approximately 5,000. One infected person will produce about 2.5 million particles per 8-hour period just from breathing. A symptomatic person coughing 10 times per 8-hour period will generate another 750,0000 particles at 75,000 particles per cough (see William et al).

This totals 3.25 million particles per 8-hour period, generating sufficient particles to infect 216 people with a viral load of 15,000 particles per person and 648 at 5,000 particles per person. The range of particles generated by an individual varies greatly, however given sufficient time in an enclosed space, any symptomatic person can generate enough particles to infect many people.

As previously stated, coronavirus particles will remain in the air for days in an enclosed space unless the particles are removed by ventilation.

How long does it take for one person to infect another in a 10x10x10 room?

The particles most likely to be absorbed in the alveolar region contain only a few instances of the corona virus (see section 1.4 of this document). Therefore, several hours may be required to generate sufficient particles and for the subsequent deposition in the lungs of the person breathing the corona virus laden aerosol particle.

The most important element of this paper is the calculation of the particle size most likely to deposit in the alveolar region of the lungs (the size of a few corona virus particles). Our calculations correspond to measurements of particle size deposition by the pharmaceutical industry for inhalers and prior studies regarding deposition.

The volume of a breath is a 0.5 liters per breath or 6 liters per minute for an average adult. Table 4 of Appendix A shows the time required for a group of people of various size to exchange the total volume of air in a room. 1 infected person would fill an entire 10x10x10 (1,000 cubic feet) room with 6,500 particles per cubic foot in 78.62 hours. In 2 hours, the room would contain an average of 165 particles per cubic foot from one symptomatic individual. A person at rest breathes 0.212 cubic feet per minute therefore consuming 35 particles per minute or 2,103 particles per hour in this example. The viral load over a 4-hour period would be 8,413 particles. This viral load rate explains why the transmission cases cited in literature are frequently in the 2 to 4-hour range (see the 4 cases cited in this paper).

One of the conclusions of this paper is aerosol particles containing only a few instances of the coronavirus have the highest deposition rates in the alveoli. This explains why several hours are required to generate these aerosol particles and deposit in the alveoli of individuals in the enclosed space. This also explains why transmission occurs in nearly everyone in the room sharing the same air as the infected individual.

The aerosol-based particle transport is well understood. The deposition in the lungs is well understood. The viral loading is well understood. It is time for the CDC to acknowledge aerosol-based transmission and the appropriate risk reduction measures. The appropriate risk reduction is managing the air pathway rather than six feet of distance for indoor aerosol-based transmission. The appropriate measure is fever screening for any public settings to eliminate symptomatic individuals from enclosed spaces. Let's start saving lives and addressing the underlying science.

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SECTION 1.0 PARTICLE TRANSPORT AND DEPOSITION

The purpose of this introduction to the actual calculations for particle transport is to show that the same principals governing coronavirus particles govern all particles. The collection/deposition is extremely well documented and understood on a theoretical and empirical level. There are no mysterious or "not well understood" aspects of particle transport and deposition. The WHO and CDC simply refuse to acknowledge these basic scientific principals well understood for decades.

Relating traditional environmental engineering controls to COVID-19 requires grouping particles by transport properties into the following classes of particles covered in this paper,

1. Very large droplets dominated by Newton's law, >1350-micron
2. Small droplets traveling further due to effects of Stokes' law, <1350 and >100-micron
3. Aerosol particles dominated by Stokes' Law, <100 and >7-micron
4. Aerosol particles primarily effected by Cunningham Slip, <7 and >0.068-micron
5. Particles dominated by diffusion. <0.068-micron

PARTICLE TRANSPORT

The transport properties of a particle are characterized by the particle's interaction with surrounding molecules. The size of an aerosol particle is the fundamental characteristic that determines its transport properties and the equations used to calculate them. The ranges of interest include,

Below are some characteristics of interest,

- Relaxation Time: Time required for a particle to transition for initial velocity to settling velocity.
- Stopping Distance: Distance required for a particle with initial horizontal velocity, V_{0x}, to reach V_x=0 due to external forces. Distance covered during the relaxation time.
- Settling (Sedimentation) Velocity: How fast the particle will fall to the ground. Sometimes referred to as Particle Settling/ Terminal Velocity in a fluid. Forces due to Drag/lift = Inertial / gravitational force.

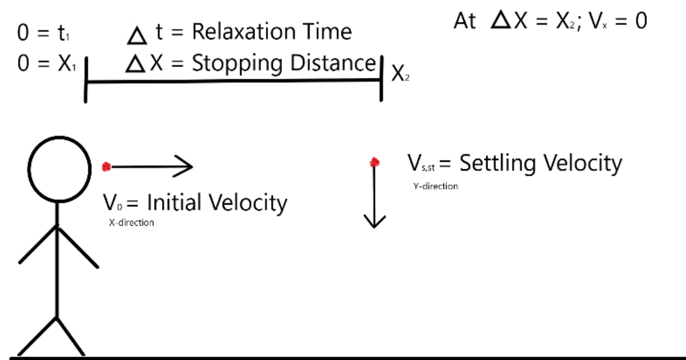


Figure 5. Relaxation Time, Stopping Distance, & Settling Velocity

This is roughly the basis for the "6 ft" of social distancing. The actual distance traveled for each particle is unique and could easily be greater than 6ft. A better approximation for a safe social distance may be ~30ft.

		Stopping Distance (Meters)					At Height = 2m
Particle Size (Micron)	Relaxation Time (s)	Vo = 5m/s	Vo = 10m/s	Vo = 22m/s	Vo = 40m/s	Settling Velocity (m/s)	Settling Time (Seconds)
0.068	5.55E-08	2.77E-07	5.55E-07	1.22E-06	2.22E-06	0.00	3.67E+06
7	1.52E-04	7.58E-04	1.52E-03	3.33E-03	6.06E-03	1.49E-03	1.35E+03
100	0.030	0.151	0.302	0.665	1.209	0.297	6.74E+00
750	0.300	1.501	3.003	6.606	18.017	2.95E+00	6.79E-01
1350	0.587	2.934	5.869	12.911	23.475	5.757	3.47E-01

Table A2. Stopping Distance at varying V_0

Coughing Individual: 2 Meters Tall

Larger particles land on nearby surfaces quickly, anything over 500-micron will be airborne less than 1 second. (See Appendix A.)

A 100-micron particle will fall for about 6.7 seconds in still air can travel about 6ft with no assistance from additional airflow.

Particles less than 100-micron have the potential to be entrained in the airflow pathway for some time and particles <50-micron may not settle, dependent on particle size and indoor airflow.

Particles smaller than 7-micron are easily entrained in the airflow pathway, rather than settling to the ground. They can stay suspended in air and replication-competent for extended periods (Doremalen et al., 2020); therefore, Social Distancing will not mitigate risk from particles this size.

Particle Deposition

Fundamental to understanding particle transport and deposition is the idea that particles similar in size to the mean distance between molecules in the air will be difficult to remove. Molecules of oxygen and nitrogen in the air are about 68 angstroms or 0.068 microns apart on average. Particles much smaller than 0.068 microns will not run into the oxygen and nitrogen molecules and will therefore behave randomly just like molecules. Particles slightly larger will slip through the air while still being influenced by the flow of air and difficult to remove. Very large particles will be easier to remove based inertial forces. The basic idea that very large and very small particles are easiest to remove is shown in the chart below and described in the text from a classic environmental engineering text.

Explain why nearly all particle size collection efficiency curves for high-efficiency control devices take the form shown in Figure 64.

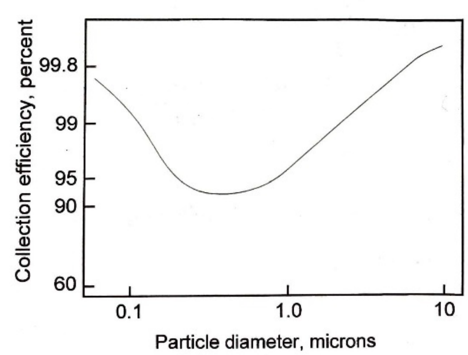


Figure 1. Effect of particle size on collector efficiency

"The collection efficiency for particulate control increases with increasing particle size over nearly the entire particle size range. However, for particles less than approximately 1.0 micron, the trend reverses and efficiency will increase with decreasing size. This phenomenon is experienced by almost all efficiency control devices, e.g., baghouses, venturi scrubbers, electrostatic precipitators, etc., and arises primarily because of molecular diffusion effects. The random, chaotic motion of submicron particles, similar to that predicted by the kinetic theory of gasses, becomes more pronounced as the particle size decreases and approaches the molecular diameter of gasses, resulting in higher efficiencies. This becomes an important consideration for systems requiring extremely high efficiencies, e.g., greater than 99.5%" (Reynolds, 2002)

The human respiratory system is a mechanical collector for particles in air. The lungs are subject to Newton's law, Stokes law and diffusion just like any particulate matter control device. Visualize the lungs as a two-stage filter. The first stage is extrathoracic, the mouth or nose, and the second stage is the pulmonary region. The two collectors are connected by the tracheobronchial region.
Figure 2 and 3 show the deposition or "collection efficiencies" of all three of these regions.

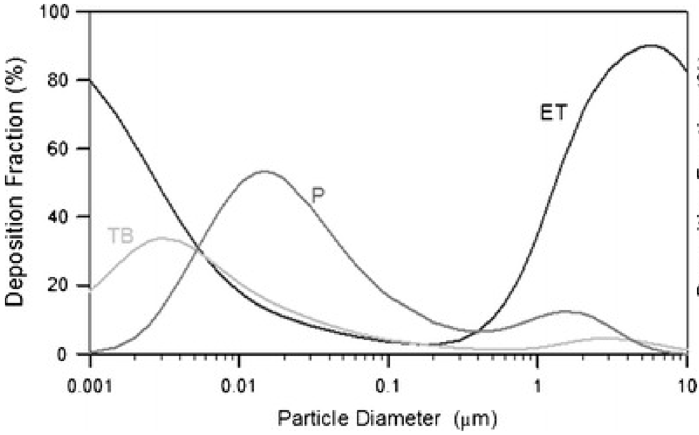


Figure 2. Nasal Breathing, Deposition as a function of Particle Diameter (Cheng et al., 2014)

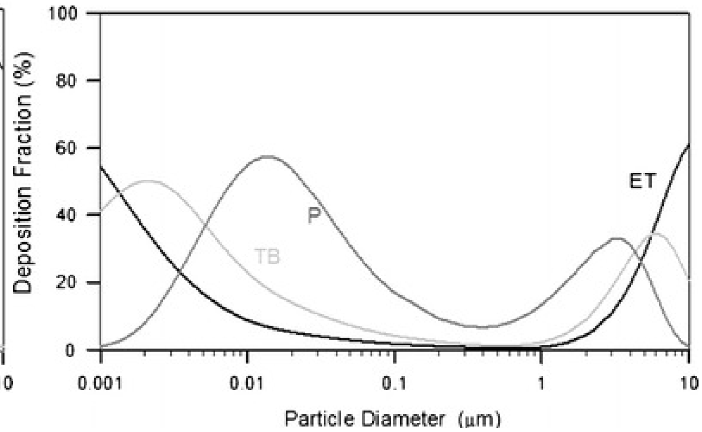


Figure 3. Oral Breathing, Deposition as a function of Particle Diameter (Cheng et al., 2014)

The very large and very small particles have high removal/deposition in the extrathoracic region. More so for nasal breathing than mouth breathing as would be expected given the nose is for breathing and the mouth for eating. This agrees with the finding from Stilianakis & Drossinos (2010), droplets with $d > 8$ μm deposit almost exclusively in the extrathoracic region, whereas droplets with $d < 4$ μm may reach the alveolar region.

The tracheobronchial region is not designed to remove particles. As will be explained in Section 1.5, the random nature of diffusion results in removal/deposition efficiencies dependent on path length. Given the long pathway for the tracheobronchial region, most of the particles well below 0.068 are removed in the extrathoracic and tracheobronchial region. See the Brownian portion of flow and particle size in Appendix A. Note also, the length of the nasal passageway is longer and therefore has higher removal efficiencies for the smallest particles which are subject to diffusion.

The pulmonary region has the highest percentage deposition for the particles in the same size range as the mean distance between air particles. Particles similar in size to that of the mean distance between molecules in air have very low efficiencies due to the phenomenon of Cunningham slip described in Section 1.4. The extrathoracic and tracheobronchial regions removed very few of these particles. Thus, the bulk of these particles make the journey deep into the lungs. The corona virus (and several clumped together) are just the right size to not be filtered out by the nose, throat or upper lungs. These particles make it all the way to the alveoli to enter the blood stream. Nature made viruses just the right size to "slip" past our particle collectors.

Relating traditional environmental engineering controls to COVID-19 requires grouping particles by transport properties into five classes of particles covered in this paper;

1. Very large droplets dominated by Newton's law, >1350-micron
2. Small droplets traveling further due to effects of Stokes' law, <1350 and >100-micron
3. Aerosol particles dominated by Stokes' Law, <100 and >7-micron
4. Aerosol particles primarily effected by Cunningham Slip, <7 and >0.068-micron
5. Particles dominated by diffusion. <0.068-micron

SECTION 1.1 VERY LARGE PARTICLES – NEWTON'S LAW REGION

- **The largest particles fall to the floor quickly. These particles are in the range of millimeters, rather than microns as with most of the particles described in this discussion. These particles are emitted with significant size and velocity, resulting in a high Reynolds Number. The particles are dominated by Newton's law. These particles are sometimes referred to as "droplets" in the news.**

Very few if any particles in a public setting are governed by Newton's law. To understand why, consider a particle of 50 microns is visible to the human eye. A particle is subject to Newton's law if the Reynold's number is over 500. Yet a 50-micron particle only has a Reynold's number of 0.242. See Table 1 at the end of this paper. The lower bound for a particle subject to Newton's law is around 1,350 microns. This particle would be easily visible. No human of sound mind would stand next to someone spitting 1,350-micron particles.

In addition to the lack of presence of these particles in most settings, consider that these large particles are removed in the extrathoracic and tracheobronchial region and do not make it to the pulmonary region. See Figure 2 Cheng (2014), article in the introduction to this section. Particles much smaller are removed at over 99% in the tracheobronchial and extrathoracic region. Deposition in the pulmonary region is an asymptote by 10 microns.

In summary, the particles would not actually exist in any reasonable public setting. Second, the particles would be removed before the alveolar region in the respiratory pathway.

<u>Equation for Very Large Particles, Newton's Law for Particle Settling Velocity:</u>

$$\boldsymbol{v = 1.74\left(\frac{g d_p \rho_p}{\rho}\right)^{0.5}},$$ (Reynolds, 2002) (Eq.1)

These particles are responsible for Fomite-based transmission; however, they are not carried by the airflow pathway and for the most part do not enter the respiratory track. These droplets are clearly visible and have a size greater than 1mm. As previously stated, very few if any particles in a real-world setting would ever be subject to Newton's law (airborne droplets).

What this means in real terms is that a person would need to be talking in a way such that visible particles were coming out of their mouth to be subject to Newton's law or "airborne" "droplets". Social or Physical distancing would be appropriate for these particles. In the real world, no sound person would stand next to someone visibly spewing particles into the surroundings. In the United States, spitting in public is not common. Spitting in public is more common in China and this may be appropriate as guidance there.

SECTION 1.2 <1350 AND >100-MICRON RANGE – INTERMEDIATE REGION

- **An intermediate equation, comprised of Newton's and Stokes' laws, governs particle transport in this range.**

Intermediate Law for Particle Settling Velocity:

$$\boldsymbol{v} = \mathbf{0.153}\left(\frac{g^{0.71}{d_p}^{1.14}{\rho_p}^{0.71}}{\mu^{0.43}\rho^{0.29}}\right), \qquad \text{(Reynolds, 2002)} \qquad \text{(Eq.2)}$$

Larger particles in this range will travel a distance but are too bulky to avoid some objects. Thus, have a higher probability of crashing into whatever is in the pathway. (door, wall, face, floor, ceiling, etc.)

Smaller particles in this range will only crash into something when there is a change in direction in the pathway (a tabletop, a turn in a vent, a hair follicle in your nose, your tongue). These particles are dominated by Stokes' law to an even greater degree.

An intermediate equation, comprised of Newton's and Stokes' laws, governs transport of particles in this range. These are removed by the tracheobronchial region, cilia, nose hairs and mucous in the nose and mouth.

SECTION 1.3 <100 AND >7.0-MICRON RANGE – STOKES'S LAW REGION

- **Particles in this range are no longer governed by Newton's Law for Particle Settling Velocity. Due to the small size, aerosol particles are governed by Stokes' Law.**

Stokes' Law for Particle Settling Velocity:

$$\boldsymbol{v} = \frac{g{d_p}^2\rho_p}{18\mu}, \qquad \text{(Reynolds, 2002)} \qquad \text{(Eq 3)}$$

These very small particles, sometimes referred to as aerosols, are very quickly entrained in the airflow pathway. They will change direction with the airflow until encountering and being trapped a small space, such as human alveoli. (Think of a dead end on a racetrack or the alveolar region of the lungs.)

Particles of less than 4 microns are considered "aerosols" by the American Conference of Governmental Industrial Hygienist (ACGIH). For purposes of this paper, we consider any particle dominated by Stokes' Law or Diffusion to be an aerosol. We recognize the importance of particles governed by Cunningham slip given the high deposition rates in the alveolar region.

Think of particles in the Stokes' law region as dust behind a truck on a dirt road, which floats because the force due to lift is greater than the force due to gravity acting on the particle. Some of the dust will settle near where it was kicked up, and some of the dust is carried away by wind and deposited elsewhere. These are important concepts when it comes to the coronavirus and particles. While all these particles are airborne, those governed by newtons law are called droplets by media; those particles governed by Stokes' law are referred to as aerosols. This is a critical distinction that CDC guidelines have failed to address.

SECTION 1.4 <7.0 AND >0.068-MICRON RANGE – CUNNINGHAM SLIP & KNUDSEN REGION

These extremely small particles are still governed by Stokes' Law but require that correction factor $\boldsymbol{C_s}$, *Cunningham Slip Correction Factor*, must be added to account for particles "*slipping*" between nearby molecules, rather than pushing them out of the way. Particles in this range all have very small settling velocities and are easily entrained in and transported by relatively weak airflow pathways, especially the largest particles in range.

The smallest of these may slip out of the airflow pathway during transport due to high slip. This will lead to deposition before the alveolar region. This is characteristic of diffusion and is covered in the next section. Submicron particles are governed by Cunningham slip, Knudsen's number, and the laws of diffusion.

Stokes' Law for Particle Settling Velocity:

$\boldsymbol{v} = \frac{g d_p{}^2 \rho_p}{18\mu} \boldsymbol{C_s}$ (Reynolds, 2002) (Eq.4)

$\boldsymbol{C_s} = \mathbf{1} + (\mathbf{2}\boldsymbol{A}\frac{\lambda}{d_p})$ (Reynolds, 2002) (Eq.4.1)

$Where\ A = 1.257 + 0.4e^{-1.10\frac{d_p}{2\lambda}}$ (Reynolds, 2002) (Eq.4.2)

These particles tend to be the most dangerous, as they will stay entrained in the airflow pathway and may very well will continue to follow that path through the respiratory system. Nearly 100% deposition in the pulmonary or alveolar region can be seen for 2- or 3-micron size particles. The particles will not run into celia and will navigate the pathways in the bronchial region leading all the way to the alveoli. This results in high deposition for particles in this range.

When "*Kn*" is low, the particle is larger than the path between molecules. Thus, the larger particle will be "pushed" along the air flow pathway. Particles low, non-zero "*Kn*" will experience very high deposition.

When "*Kn*" is high, the particle is much smaller than the free path and will not collide with other particles. This approaches diffusion & results in low deposition due to fewer particles of this size entering the respiratory system. When "*Kn"* > 10, the particle is in diffusion and experiences fully random, Brownian motion. Fewer of these Brownian particles will reach the respiratory system due to this random motion.

Knudson Number Equation:

$\boldsymbol{Kn} = \boldsymbol{\lambda}/\boldsymbol{d_p}$ (Reynolds, 2002) (Eq.5)

Where $\lambda = Mean\ Free\ Path = 68\ nm\ (Jennings, 1988),\quad d_p = Particle\ Diameter$

The range of Knudsen's number for a single COVID-19 virus laden particle with no water molecules is approximately (Mean Free Path between molecules in air/diameter of coronavirus) 68/60 or 1.13 to 68/140 or 0.49. Water molecules attached to the COVID-19 laden particle will increase the size and decrease the Knudsen's number.

A particle leaving an infected person containing 2 instances of COVID-19 (0.12 to 0.28 microns in diameter) have a Knudsen's number ranging from 68/120 (0.567) to 68/280 (0.242).

A particle leaving an infected person containing 3 instances of COVID-19 (0.24 to 0.42 microns in diameter) have a Knudsen's number ranging from 68/240 (0.283) to 68/420 (0.161).

Particles ranging from 0.7 to 5 microns will have the highest absorption rate as these particles are in the Cunningham Slip range. The Cunningham Slip range corresponds to particles with 1, 2, or 3 instances of the coronavirus. Why is all this information about particle size and deposition important?

An infected person in an enclosed space will fill the room with aerosol particles. If a non-infected person is in the room for several hours, they will inhale a sufficient number of particles to contract the virus.

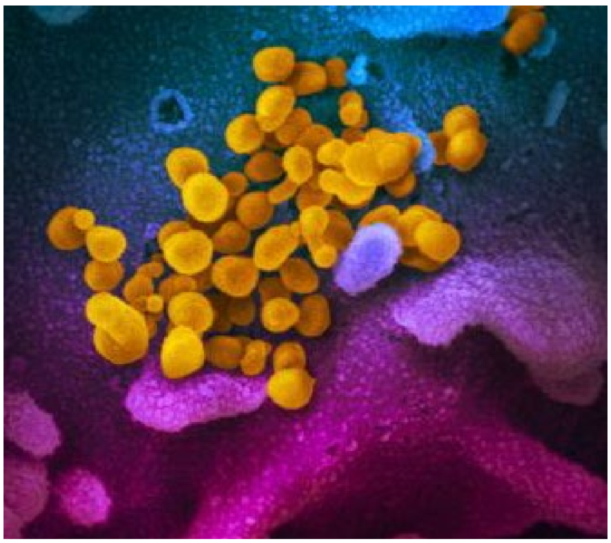
The viral load from any single particle will be very low (1, 2 or 3 instances of the corona virus). This means an extended exposure is required to absorb enough particles to contract the virus. This is consistent with most documented cases involving several hours of exposure (Washington Choir was 4 hours of exposure, the Arizona teacher was 2 plus hours, the Chicago birthday party was an afternoon long event). A casual passing does not create enough exposure time to breathe in a sufficient viral load. (thus, the lack of people contracting the virus from visiting a grocery store for example).

The mathematics of this paper confirm what we see in case studies. Outdoor events have a high fresh air rate and therefore do not have a sufficient accumulation of aerosol particles to create a transmission event.

Figures 2 and 3 in the introduction to this section show deposition as a function of particle size.

In a human, particles subject to Cunningham slip and Knudsen Flow are trapped in alveoli in the lung. This is where the COVID-19 particle may infect the white blood cells. Once COVID-19 reaches the white blood cells and microphage the story of transmission ends, and the story of infection begins.

The COVID-19 virus is well sized size for Cunningham slip explaining why the virus is so opportunistic. The image below shows the coronavirus exist in single form or clumps of two, three or four instances of the virus. This conforms to Cunningham slip numbers with maximum absorption in the alveoli.



To further understand this phenomenon, consider that the mean distance between oxygen and nitrogen particles in the air is 68 nanometers. This is a very critical number. Particles in this range are large enough to be influenced by the flow of the nitrogen and oxygen molecules in a breath of air as the particles are larger than the mean distance between molecules in air.

The Coronavirus is 60 to 140 nanometers in diameter. The following reference states 100 nanometers and is based on Scanning Electron Microscopes (SEM) and Transmission Electron Microscopes (TEM)

Figure 6. SEM Image shows clumps of Coronavirus particles. Image: *SARS-COV-2, NIAID-RML (NAID, 14)*

SECTION 1.5 <0.068 MICRON RANGE – DIFFUSION RANGE

These particles are the same size or smaller than the mean distance between molecules in the air. Therefore, they will behave much like molecules which are governed by diffusion. The random motion (Brownian Motion) of the particle and the molecules in the air cause both the molecules and the particles to impact the upper respiratory track. In short, these particles move randomly and not with the air flow pathway due to the very small nature of the particle relative to the distance between the molecules in the air.

See Figure 2 and 3 from the Yung Sung Cheng article regarding deposition in the respiratory tract for a confirmation of the Brownian motion/random motion phenomenon. The longest pathways (Tracheobronchial and Extrathoracic) region account for nearly 100% of the deposition for particles subject to Brownian flow (see also Figures 2 and 3).

Particles small enough to be primarily governed by diffusion are also of little concern as the particles are too small to be a coronavirus laden particle.

Why is all that important? Let's relate the basic science of particles to the transfer of COVID-19 and the prevention (risk reduction measures) of the transmission of the disease.

SECTION 2.0 RISK REDUCTION MEASURES PER PARTICLE SIZE

The importance of these particle transport and deposition of the coronavirus transmission further breaks down like this.

What is the importance of coronavirus being transmitted as an aerosol? Risk reduction for aerosols relies on managing the pathway of the corona virus laden aerosol particles. This section documents that aerosol particles will follow the pathway of the air flow in a room rather than falling to the surface. One important component to manage is the placement of people in a room relative to the air pathway. Social distancing means nothing.

In the illustration below, the placement of the person in front of the vent causes all of the particles generated by the speaker to broadcast over the classroom participants. This is a worst-case scenario. Placing the speaker in front of the door means not a single classroom participant is exposed to the aerosol particles generated by the speaker. The person in the middle of the room is equidistant from the speaker in both scenarios. However, in scenario 1, the exposure is high. In scenario 2, there is no exposure. Note that the distance from the speaker has no impact on the risk of transmission. In summary, pathway means everything when dealing with aerosols. Social or physical distance means nothing for aerosol transmission.

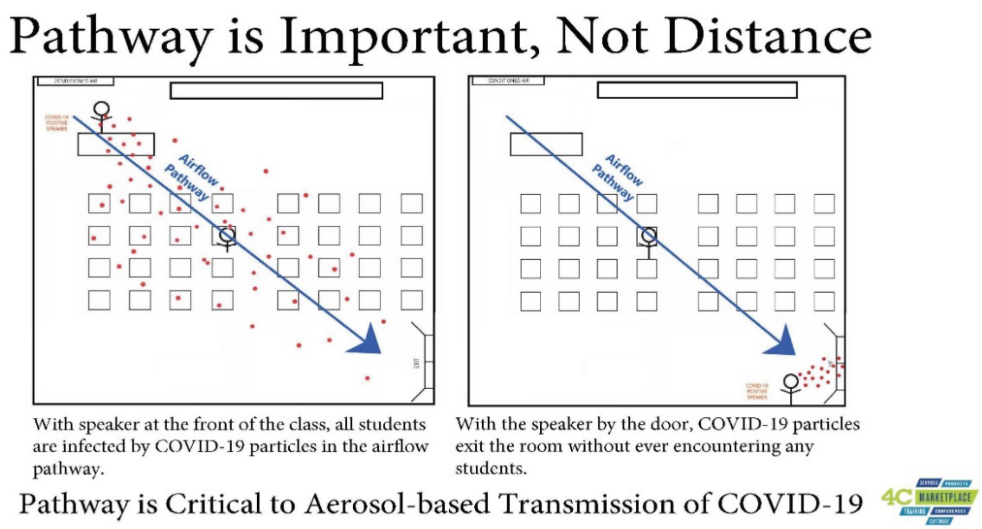


Figure 7. Classroom application for management of forced ventilation and airflow pathway.

The particle size distribution for a symptomatic versus asymptomatic person is an important factor to determine if these particles play a significant role in the transmission of the virus. A recent study from WHO shows how transmission rate varies between asymptomatic and symptomatic individuals, "individuals without symptoms are less likely to transmit the virus than those who develop symptoms. Four individual studies from Brunei, Guangzhou China, Taiwan China and the Republic of Korea found that between 0% and 2.2% of people with asymptomatic infection infected anyone else, compared to 0.8%-15.4% of people with symptoms.(10, 72, 86, 87)" (WHO, 2020)

The number of particles may be greatest at the initial onset of a cough given the accumulation of the coronavirus in the respiratory system. "Viral shedding is maximal at the time when symptoms appear, and decreases exponentially thereafter" (Douglas, 1975; Hall et al., 1979). As with other viruses, the number is likely highest at the onset of symptoms as the body has only just begun to fight off the infection.

Similar analysis can be applied to the cabin of aircraft. Is air travel a breeding ground for Coronavirus?

Evidence, although limited, suggests that, the risk of virus transmission on board aircraft is low even without special measures. A recent public report shows that a flight on 31 March from USA to China Taipei with 12 people subsequently confirmed to be symptomatic at the time of flight, generated no secondary confirmed cases from the 328 other passengers and crew members, who all tested negative. (IATA, 2020)

In an interview with Travel and Leisure, Boeing's Dr. David R. Space, an associate technical fellow in the Boeing Commercial Airplanes Environmental Controls Systems group, explains aircraft ventilation. 50% of cabin air is recirculated after it has been through a specialized HEPA (high efficiency particulate air) filter. Outside air is compressed to maintain suitable cabin air pressure, resulting in a warmer gas than before. Then the compressed air is mixed with the 50% cabin air being recirculated. The other 50% of cabin air is thrown overboard. (Garcia, 2017)

The mixed air then travels through air ducts on the plane, from back to front, and to connecting ducts, where the ceiling meets the sideboard. At the same time, air leaves the cabin through return air grills, where the cabin meets the floor. According to Space, For the cabin air, "There are between 12 to15 air changes in an hour and 25 to 30 cycles through a HEPA filter." Meaning the airflow pathway for each person is extremely short and well filtered, thus lowering the risk of transmission in-flight.

Are HEPA filters effective for Coronavirus?

As shown in figure 8, HEPA filter efficiency is well documented, and exhibit expected behavior regarding removal efficiency. At particle sizes between 0.1 and 1-micron, as the effects of diffusion come into play, removal efficiency decreases. This agrees with figure 1, as HEPA filters are mechanical collectors.

All of this considered, HEPA filters maintain >99% removal efficiency for coronavirus particle sizes.

The phenomena associated with particulate matter removal by HEPA media filters and packed beds of granular material have been reviewed relative to their efficacy for removing fine (<2.5 μm) and ultrafine (<0.01 μm) sized particulate matter. The ultrafine particulate range constitutes the range defined as nanoparticulates. When used alone, HEPA-rated media provides superior performance for removing virtually 100% of particulates. (Perry et al. 2016)

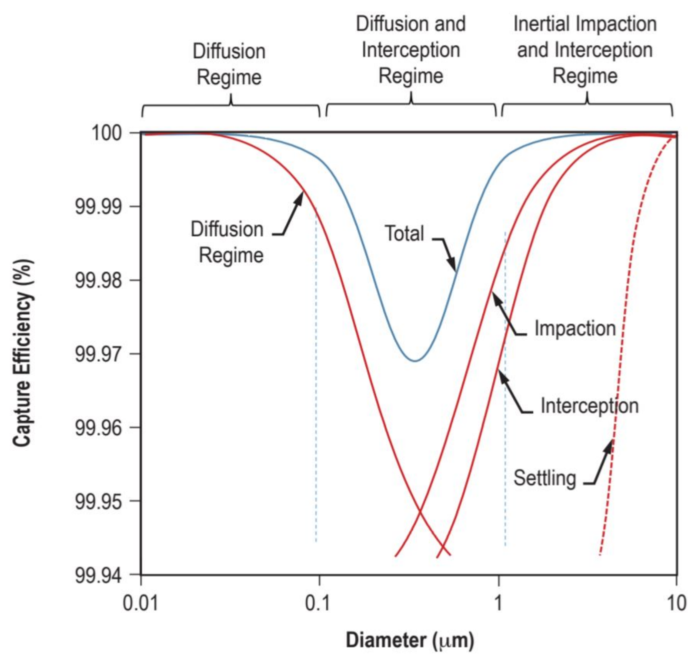


Figure 8. HEPA Filter removal efficiency as a function of particle diameter.

High transmission rates and/or large transmission events have not been observed among airline passengers with appreciable regularity. High transmission in individuals with direct contact and Large transmission events in a closed space may be expected in the case of indirect/fomite-based and aerosol-based transmission respectively, but neither has proven prevalent. The mathematics in this paper support the observation of low transmission rates among airlines, considering filtering mechanisms as well as in-flight airflow pathway.

Section 2.1 Very Large Particles – Newton's Law Region

- **Very large airborne droplets fall to the floor quickly (>1350 microns),**

The actual distance traveled by each particle is governed primarily by its geometry and by gravity, the speed and direction of the particle as projected by the breathing, talking, singing, cheering, or coughing individual. For a visual, this is more akin to throwing a marble or dropping a marble when it comes to determining the distance traveled.

The force of gravity pulling the particle to the earth initially is much larger for this large particle than the lift created by air flow and therefore the settling velocity is higher. However, if particles this size are released with considerable velocity, they will travel a great distance.

When these particles land on a surface and a susceptible individual touches the surface a "Fomite" based transmission may occur. Some of these large particles, sometimes referred to in coronavirus lingo as "droplets", may also land on a susceptible individual. Wearing a mask will prevent projecting particles on people during a cough or sneeze. See Section 1. Particle Transport for more on removal efficiency

An asymptomatic person may not generate enough velocity for the particles to travel very far during normal breathing and is not the primary means of transmission for the coronavirus.

The number of particles of this size will also be much greater when a symptomatic, infected individual coughs. A cough creates an air flow with sufficient force to project the particle (throw the marble). Once the particle leaves the body gravity takes over.

This may be why symptomatic individuals may cause the bulk of transmission events.

This is supported by a report first published by the CDC on April 1, 2020 as an Morbidity and Mortality Weekly Report Early Release included one study of 157 locally acquired COVID-19 cases in Singapore, transmission during the incubation period was estimated to account for 6.4 percent; in such cases, the exposures occurred one to three days prior to symptom development. (Ghinai et. Al., 2020)

The spread of coronavirus caused by large airborne droplets may be reduced by;

1.) Febrile Screening reduces the number of particles in the air by eliminating symptomatic individuals from social and workplace gatherings,
2.) Wearing masks to create a protective barrier and to reduce the number of particles in the droplet cloud. Wearing a mask will prevent projecting large particles on people during a cough or sneeze. (see graph above),
3.) Social distancing to avoid the particles landing on your face or entering your breathing space,
4.) Sanitizing surfaces where the particles land.
5.) Surface Testing using reverse transcription quantitative polymerase chain reaction (RT-qPCR) testing to determine fomite-based transmission.

Section 2.2 <1350 and >100 Micron Range – Intermediate Region

- **Particles <1350 and >100 microns will travel a distance but are too bulky to avoid objects, thus crashing into whatever is in the pathway. (door, wall, face, floor, ceiling, tracheobronchial tract, etc.)**

The settling velocity for a 100-micron particle is 0.297 m/s. For a 1.5-meter person, the particle will take 5.05 seconds to reach the ground in the absence of air flow. The particles on the upper end of this range will be deposited on surfaces and people.

Social distancing will help to mitigate the risk of transmission from the particles of this size.

The particle size distribution for a symptomatic versus asymptomatic person is an important factor to determine if these particles play a significant role in the transmission of the virus. A recent study from WHO shows how transmission rate varies between asymptomatic and symptomatic individuals, "individuals without symptoms are less likely to transmit the virus than those who develop symptoms. Four individual studies from Brunei, Guangzhou China, Taiwan China and the Republic of Korea found that between 0% and 2.2% of people with asymptomatic infection infected anyone else, compared to 0.8%-15.4% of people with symptoms.(10, 72, 86, 87)" (WHO, 2020)

The percent of cases resulting from this sized particle is so important because forced and natural convection largely determines the pathway of these particles. Febrile screening several times per day at work settings may be an appropriate means of reducing the transmission of COVID-19.

Particles in this range are likely the largest contributors to,

1.)"Fomite" based transmission by settling on a surface, and

2.) droplet-based transmission when deposition of droplets occurs on the face of a potentially infected person or they are inhaled directly after being emitted.

The spread of coronavirus caused by >100 microns particles may be reduced by:

1.) Febrile Screening reduces the number of particles in the air by eliminating symptomatic individuals from social and workplace gatherings,

2.) Sanitizing surfaces where the particles land,

3.) Wearing masks to create a protective barrier and to reduce the number of particles in the droplet cloud. Wearing a mask will prevent projecting large particles on people during a cough or sneeze. (see graph above),

4.) Managing the forced and natural convection to prevent smaller particles from encountering individuals.

5.) Social or physical distancing to allow largest particles to settle prior to contact.

6.) Measuring particulate (>10, >2.5 and >0.3) micron as a surrogate for airborne (droplet and aerosol) virus concentrations reduces the risk of aerosol particle build up in a room.

7.) Surface Testing using reverse transcription quantitative polymerase chain reaction (RT-qPCR) testing to determine fomite-based transmission.

SECTION 2.3 <100 AND >7.0 MICRON RANGE – STOKES'S LAW REGION

- **Particles in the <100 and >7.0 microns range will only crash into something when there is a change in direction in the pathway (turn in a vent, a hair follicle in your nose, your tongue). Think of this like a car taking a turn too fast and crashing into the wall.**

These particles will travel further than either of the aforementioned particles sizes. The force of lift is far greater than the force of gravity for these particles. In fact, these particles will remain airborne until removed from the air by running into something (air filters, our noses or mouth, rain). These particles while remaining airborne are still too bulky to change direction when the air flow changes direction. The air goes in our nose and towards our lungs. These particles crash into the hair in our nose or other mechanisms in our nose and mouth designed to eliminate particles (think mucus and saliva).

The settling velocity of a 58-micron particle is 0.1 m/s. The typical average air flow from convection is 0.1m/s. This means particles larger than 58 microns will eventually settle and deposit on surfaces.

This distinction between airborne or aerosol versus droplet is relevant to social distancing. Social distancing does nothing for airborne or aerosol particles. Let me explain the distinction. A symptomatic person sits in a poorly ventilated room for three hours and coughs several times. The room is now filled with aerosol particles. If a person were sitting for three hours next to the symptomatic, infected individual or ten feet away – the outcome is the same – a transmission event. The air in the room is filled with coronavirus particles. The airborne virus may even infect the next group of people to use the room for three hours where zero social interaction has occurred.

The aerosol scenario is very different than the droplet-based scenario many guidelines frame their recommendations in. Could one person be blathering and spitting droplet particles (the ones that fall to the ground) to infect 50 people? Highly doubtful. However, in an aerosol scenario a single person could infect 100s of people sharing airspace filled with the same virus laden aerosol particle cloud. The choir case-study is, in my opinion, an aerosol-based transmission event that resulted in more than 50 people infected by one person in a single event.

Social distancing (6 ft or 10 ft or whatever distance) has zero impact on aerosol-based transmission.

The removal of these particles or placement of the individuals determine if a transmission event occurs. For example, imagine the following scenario. The speaker is at the front of the room and the ventilation is blowing from behind the speaker toward the people sitting in the chairs and the air is being recirculated (no fresh air). The people will be removing the airborne particles with their nose, mouth, Cilia and alveolar region. In the same setting, put the speaker in the back of the room next to the door, introduce fresh air, and the people in the room have close to zero exposure.

Pathway, placement, and fresh air mean everything for aerosol-based transmission. Distance means nothing.

Natural and Forced convection will impact the pathway traveled by these particles. Pathway is the germane factor for airborne particles. Elimination from the breathing space is also critical. Social distance has no effect.

A cough creates an air flow with sufficient force to project the particle into the air space. Once airborne, these particles do not fall to the ground. The number may also be highest at the onset of symptoms given the accumulation of coronavirus in the respiratory system; as the body has not begun to fight off the infection or reject the particles through coughing and spitting. The importance of symptomatic versus asymptomatic is important. Febrile screening removes symptomatic individuals from social and business settings.

If aerosol-based transmission is the primary mode of transmission and symptomatic individuals generate far more aerosol than asymptomatic individuals, then febrile screening is the number one prevention method.

The spread of coronavirus caused by particles <100 and >7 microns may be reduced by:

1.) Febrile Screening reduces the number of particles in the air by eliminating symptomatic individuals from social and workplace gatherings
2.) Wearing masks to create a protective barrier and to reduce the number of droplet and aerosol particles in the air. Wearing a mask will prevent projecting large particles on people during a cough or sneeze. Wearing a mask will not prevent aerosol-based transmission events as the corona virus is less than 1 micron in diameter. Masks are effective for droplet events but do not provide protection from aerosol-based transmission in enclosed spaces for meetings of 2 hours or more in duration.
3.) Managing the forced and natural convection to prevent these particles from encountering individuals.
4.) Measuring particulate (>10, >2.5 and >0.3) micron as a surrogate for airborne (droplet and aerosol) virus concentrations reduces the risk of aerosol particle build up in a room.
5.) Surface Testing using reverse transcription quantitative polymerase chain reaction (RT-qPCR) testing to determine fomite-based transmission.

SECTION 2.4 <7.0 AND >0.068 MICRON RANGE – CUNNINGHAM SLIP & KNUDSEN REGION

- **<7.0-micron particles will change direction with the air current until a small space is encountered. (Think of a dead end on a racetrack.) In a human, this is the alveolus in the lung.**

These particles will travel further than particle sizes previously mentioned. The force of lift is far greater than the force of gravity for these particles. In fact, these particles will remain airborne until removed from the air (specialty air filters, alveoli in our lungs) or discharged to the outdoor air through ventilation. These particles are small enough to avoid running into surfaces given a change in direction of the air flow but not so small to have random movement through Brownian motion like the particles smaller than 0.068 microns.

Again, social distancing will not stop transmission from these particles, their pathway is critical. The particles will remain suspended in air for extended periods of time. Even while wearing a mask and social distancing, one could be infected just by sitting in an empty room, alone, if a symptomatic individual had previously filled the volume of air in the room with COVID-19 laden aerosols. The virus may remain infectious for 3 to 16 hours after the symptomatic individual has left. (Doremalen et al., 2020)

This is very different from droplet-based transmission as the precautions are completely different. Particles in this range, particularly those between 0.1 and 1-micron are the toughest to remove with any mechanical efficiency collector. (See figure 8). Mask wearing is great for slowing the spread of COVID-19 from droplets but will do nothing to stop infectious aerosol-based particles from entering or exiting the respiratory system.

Following the guidance from the WHO or CDC, one may think they are being safe while they actually could infect 100s of people sharing the same virus laden aerosol-based particle space. The choir case-study is, in my opinion, an aerosol-based transmission event that resulted in more than 50 people infected by one person in a single event. Social distancing (6 ft or 10 ft or whatever distance) has zero impact on aerosol-based transmission.

The removal of these particles or placement of the individuals determine if a transmission event occurs. For example, imagine the following scenario. The speaker is at the front of the room and the ventilation is blowing from behind the speaker toward the people sitting in the chairs and the air is being recirculated (no fresh air). The people will be removing the airborne particles with their lungs. In the same setting, put the speaker in the back of the room next to the door, introduce fresh air, and the people in the room have close to zero exposure. Pathway, placement, and fresh air mean everything in this setting.

Pathway is again greatly influenced by Natural and Forced convection, and these particles can travel significant distances in air. Social distancing does not provide protection from this mode of transmission. Elimination of symptomatic individuals from the breathing space is critical to controlling aerosol-based transmission risk.

The particle size distribution for a symptomatic versus asymptomatic person is an important factor to determine if these particles play a significant role in the transmission of the virus. There are no definitive studies on this matter to my knowledge. Yet this is one of the key factors in the spread of the disease. The percent of cases resulting from particles <7.0 micron is so important because the forced and natural convection largely determine the pathway of these particles.

These particles are deposited in the respiratory tract. Cilia may remove the particles >1 micron and the alveolar region may remove some submicron particles.

The spread of coronavirus caused by particles <7.0 microns may be reduced by;

1.) Febrile Screening reduces the number of particles in the air by eliminating symptomatic individuals from social and workplace gatherings

2.) Managing the forced and natural convection to prevent these particles from encountering individuals.

3.) Wearing masks to create a protective barrier and to reduce the number of droplet and aerosol particles in the air. Wearing a mask will prevent projecting large particles on people during a cough or sneeze. Wearing a mask will not prevent aerosol-based transmission events as the corona virus is less than 1 micron in diameter. Masks are effective for droplet events but do not provide protection from aerosol-based transmission in enclosed spaces for meetings of 2 hours or more in duration.

4.) Measuring CO_2 concentrations as a surrogate for fresh air circulation reduces the risk of aerosol particle build up in a room.

5.) Measuring particulate (>10, >2.5 and >0.3) micron as a surrogate for airborne (droplet and aerosol) virus concentrations reduces the risk of aerosol particle build up in a room.

6.) Surface Testing using reverse transcription quantitative polymerase chain reaction (RT-qPCR) testing to determine fomite-based transmission.

SECTION 2.5 <0.068 MICRON RANGE – DIFFUSION RANGE

Particles small enough to be primarily governed by diffusion are also of little concern as the particles are too small to be a coronavirus laden particle. (Average coronavirus particle size is 100nm)

The viral load from any single particle will be very low (1, 2 or 3 instances of the corona virus). This means an extended exposure is required to absorb enough particles to contract the virus. This is consistent with most documented cases involving several hours of exposure (Washington Choir was 4 hours of exposure, the Arizona teacher was 2 plus hours, the Chicago birthday party was an afternoon long event). A casual passing does not create enough exposure time to breathe in a sufficient viral load. (thus the lack of people contracting the virus from visiting a grocery store for example).

An infected person in an enclosed space will fill the room with aerosol particles. If a non-infected person is in the room for several hours, they will inhale a sufficient number of particles to contract the virus.

The spread of coronavirus caused by particles <0.068 microns may be reduced by;

1.) Febrile Screening reduces the number of particles in the air by eliminating symptomatic individuals from social and workplace gatherings
2.) Wearing masks to create a protective barrier and to reduce the number of droplet and aerosol particles in the air. Wearing a mask will prevent projecting large particles on people during a cough or sneeze. Wearing a mask will not prevent aerosol-based transmission events as the corona virus is less than 1 micron in diameter. Masks are effective for droplet events but do not provide protection from aerosol-based transmission in enclosed spaces for meetings of 2 hours or more in duration.
3.) Measuring CO_2 concentrations as a surrogate for fresh air circulation reduces the risk of aerosol particle build up in a room.
4.) Surface Testing using reverse transcription quantitative polymerase chain reaction (RT-qPCR) testing to determine fomite-based transmission.

CONCLUSIONS

Based on empirical evidence, masks are not an effective means for reducing aerosol-based transmission. Wearing a mask for the full duration that a space is occupied is not practical. Nursing homes scenario require time for residents to eat, drink, shower, etc. It is simply not practical to wear a mask 24/7. The aerosol-based particles will remain so long as a symptomatic, infected person continues to emit aerosol particles and increase the viral load present. In a nursing home setting during an outbreak, cleaning surfaces and social distancing will not change the outcome so long as the airborne particles remain; effective solutions will require fever screening, removing the symptomatic individuals and improving airflow.

The mathematics of this paper confirm what we see in case studies. Outdoor events have a high fresh air rate and therefore are unlikely to have a sufficient accumulation of aerosol particles to create a transmission event.

The number of coronavirus particles will also be much greater (10,000 to 20 million times) when a symptomatic, infected individual coughs. Infection may require 5,000 to 15,000 of the coronavirus entities to enter the body. Each of these particles may contain multiple instances of the virus based on the size of particle.

Asymptomatic individuals do not cough and therefore have much lower exit velocities for the particles leaving the infected person. Symptomatic individuals cough generating the velocity of the particles to travel some distance. Symptomatic individuals also contain many more particles in each cough at the onset of symptoms as the body has not yet begun to fight off the infection and viral shedding is at highest. (Douglas, 1975; Hall et al., 1979).

"Widespread community transmission, as is currently being observed in the United States, requires more expansive transmission events between non-household contacts." (Ghinai I, Woods S, Ritger KA, et al., 2020) The important conclusion from this study is the 100% infection rate from extended time (greater than 3 hours in the same breathing space with a COVID 19 symptomatic person). This result only makes sense in an aerosol-based transmission scenario.

Aerosol particles containing only a few instances of the coronavirus have the highest deposition rates in the alveoli. This explains why several hours are required to generate these aerosol particles and deposit in the alveoli of individuals in the enclosed space. This also explains why transmission occurs in nearly everyone in the room sharing the same air as the infected individual.

Interestingly most viruses are less than 0.3 microns. Does this mean the transmission mode is through the alveoli where white blood cells (Microphage) encounter the genetic material of the virus? There are no references to this in the literature, however it is interesting to note there are no viruses greater than 1 micron.

Particles in a specific range, 0.01-1 micron, are the most difficult size to collect for any mechanical collector. The coronavirus is sized perfectly to fit in this range of low efficiency. Particles that are not deposited during transport to the alveolar region, may impact the "dead end" at the bottom of the respiratory tract where deposition is highest for particles the size of a 1 to 3 corona virus.

"Researchers in China studying the spread of the coronavirus outside Hubei province—ground zero for the pandemic—identified 318 clusters of three or more cases between 4 January and 11 February, only one of which originated outdoors. A study in Japan found that the risk of infection indoors is almost 19 times higher than outdoors. (Japan, which was hit early but has kept the epidemic under control, has built its COVID-19 strategy explicitly around avoiding clusters, advising citizens to avoid closed spaces and crowded conditions.)" (Kupferschmidt et al, 2020)

Eliminating clusters of people in indoor settings (specifically poorly ventilated settings with low fresh air rates and poor pathways) eliminates the setting for aerosol-based transmission. There are no super-spreading people only super-spreading conditions.

If aerosol particles are the primary mode of transmission one would expect transmission events where many people are infected in a single setting. The transmission dynamics point to aerosol-based transmission.

This conclusion (aerosol-based transmission) is the only plausible explanation of the Washington Choir case where over 50 people were infected by 1 symptomatic individual. "Droplet" particles governed by Newton's law are visible as shown in this paper. The individual in the Washington Choir case would have visibly cast particles upon over 50 people to explain this case with so called "droplet" transmission. Fomite transmission would have required the infected individual to visibly cast "droplet" particles on the food and surface touched by 50 plus people. Neither "droplet" nor fomite-based transmission are reasonable or plausible in the Washington Choir case. In addition, this paper clearly shows the exact math and science behind aerosol-based transmission. An understanding of aerosol-based transmission would clearly expect no result other than an infection of nearly every person in the Washington Choir case.

Conclusion

1.) Aerosol-based transmission is the primary mode of COVID-19 transmission.

Recommendations

1.) Fever Screening eliminates symptomatic individuals from settings where people gather and is therefore the most effective means of reducing the spread of COVID-19.

2.) Managing forced and natural convection to reduce aerosol pathways, aerosol clouds, and aerosol cloud mass is essential to reducing the spread of COVID-19 in the event an infected person is in a social gathering.

3.) Measuring CO_2 concentrations as a surrogate for fresh air circulation reduces the risk of aerosol particle build up in a room.

4.) Measuring particulate (>10, 1 and 0.1) micron as a surrogate for airborne (droplet and aerosol) virus concentrations reduces the risk of aerosol particle build up in a room.

5.) Surface Testing using reverse transcription quantitative polymerase chain reaction (RT-qPCR) testing to determine fomite-based transmission.

6.) Wearing masks to create a protective barrier and to reduce the number of droplet and aerosol particles in the air. Wearing a mask will prevent projecting large particles on people during a cough or sneeze. Wearing a mask will not prevent aerosol-based transmission events as the corona virus is less than 1 micron in diameter. Masks are effective for droplet events but do not provide protection from aerosol-based transmission in enclosed spaces for meetings of 2 hours or more in duration.

Background

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35.

APPENDIX A – PARTICLE TRANSPORT CALCULATIONS

Table A1. Particle Transport Calculations

Type or Range	Meters	*Particle Diameter Micron*	K	Regime	V,st(Cs) (m/s)	Re,st (Cs)	Cs	Kn	A	Diffusivity (SI)	Diffusivity (CCG)	Relaxation Time (s)	Stopping Distance (5)	Stopping Distance (10)	Stopping Distance (22)	Stopping Distance (60)
1 nm	1.00E-09	0.001	3.26E-05	Boltzmann	6.69E-09	4.37E-13	225.914	68.000	1.6538	5.37E-06	5.37E-02	6.82E-10	3.41E-09	6.82E-09	1.50E-08	2.73E-08
Diffusion Region	6.75E-09	0.0068	2.20E-04	Boltzmann	4.58E-08	2.02E-11	33.957	10.074	1.6357	1.20E-07	1.20E-03	4.67E-09	2.33E-08	4.67E-08	1.03E-07	1.87E-07
10 nm	1.00E-08	0.01	3.26E-04	Boltzmann	6.84E-08	4.47E-11	23.113	6.800	1.6259	5.50E-08	5.50E-04	6.98E-09	3.49E-08	6.98E-08	1.53E-07	2.79E-07
	6.00E-08	0.06	1.96E-03	Boltzmann	4.70E-07	1.84E-09	4.407	1.133	1.5032	1.75E-09	1.75E-05	4.79E-08	2.39E-07	4.79E-07	1.05E-06	1.92E-06
Mean Free Path	6.80E-08	0.068	2.22E-03	Stokes-Cs	5.44E-07	2.42E-09	3.976	1.000	1.4878	1.39E-09	1.39E-05	5.55E-08	2.77E-07	5.55E-07	1.22E-06	2.22E-06
Average Coronavirus Particle	1.00E-07	0.1	3.26E-03	Stokes-Cs	8.74E-07	5.71E-09	2.952	0.680	1.4352	7.02E-10	7.02E-06	8.91E-08	4.45E-07	8.91E-07	1.96E-06	3.56E-06
	1.20E-07	0.12	3.92E-03	Stokes-Cs	1.11E-06	8.68E-09	2.596	0.567	1.4085	5.14E-10	5.14E-06	1.13E-07	5.64E-07	1.13E-06	2.48E-06	4.51E-06
	1.40E-07	0.14	4.57E-03	Stokes-Cs	1.36E-06	1.25E-08	2.346	0.486	1.3859	3.98E-10	3.98E-06	1.39E-07	6.94E-07	1.39E-06	3.05E-06	5.55E-06
	1.80E-07	0.18	5.88E-03	Stokes-Cs	1.94E-06	2.28E-08	2.020	0.378	1.3503	2.67E-10	2.67E-06	1.98E-07	9.88E-07	1.98E-06	4.35E-06	7.90E-06
2 Average Coronavirus Particles	2.00E-07	0.2	6.53E-03	Stokes-Cs	2.26E-06	2.95E-08	1.909	0.340	1.3363	2.27E-10	2.27E-06	2.30E-07	1.15E-06	2.30E-06	5.07E-06	9.22E-06
	2.40E-07	0.24	7.83E-03	Stokes-Cs	2.98E-06	4.67E-08	1.745	0.283	1.3144	1.73E-10	1.73E-06	3.03E-07	1.52E-06	3.03E-06	6.67E-06	1.21E-05
	2.80E-07	0.28	9.14E-03	Stokes-Cs	3.79E-06	6.92E-08	1.631	0.243	1.2985	1.38E-10	1.38E-06	3.86E-07	1.93E-06	3.86E-06	8.49E-06	1.54E-05
3 Average Coronavirus Particles	3.00E-07	0.3	9.79E-03	Stokes-Cs	4.23E-06	8.28E-08	1.586	0.227	1.2923	1.26E-10	1.26E-06	4.31E-07	2.15E-06	4.31E-06	9.48E-06	1.72E-05
	4.20E-07	0.42	1.37E-02	Stokes-Cs	7.37E-06	2.02E-07	1.411	0.162	1.2704	7.99E-11	7.99E-07	7.51E-07	3.76E-06	7.51E-06	1.65E-05	3.01E-05
500 nm	5.00E-07	0.5	1.63E-02	Stokes-Cs	9.95E-06	3.25E-07	1.344	0.136	1.2640	6.39E-11	6.39E-07	1.01E-06	5.07E-06	1.01E-05	2.23E-05	4.06E-05
	6.80E-07	0.68	2.22E-02	Stokes-Cs	1.71E-05	7.61E-07	1.252	0.100	1.2586	4.38E-11	4.38E-07	1.75E-06	8.73E-06	1.75E-05	3.84E-05	6.99E-05
Beginning of High Slip Region			See Kn -->					Kn>0.1								
	8.00E-07	0.8	2.61E-02	Stokes-Cs	2.30E-05	1.20E-06	1.214	0.085	1.2576	3.61E-11	3.61E-07	2.34E-06	1.17E-05	2.34E-05	5.16E-05	9.38E-05
	1.00E-06	1	3.26E-02	Stokes-Cs	3.47E-05	2.26E-06	1.171	0.068	1.2571	2.78E-11	2.78E-07	3.53E-06	1.77E-05	3.53E-05	7.78E-05	1.41E-04
	2.50E-06	2.5	8.16E-02	Stokes-Cs	1.98E-04	3.23E-05	1.068	0.027	1.2570	1.02E-11	1.02E-07	2.02E-05	1.01E-04	2.02E-04	4.43E-04	8.06E-04
	5.00E-06	5	1.63E-01	Stokes-Cs	7.66E-04	2.50E-04	1.034	0.014	1.2570	4.92E-12	4.92E-08	7.80E-05	3.90E-04	7.80E-04	1.72E-03	3.12E-03
	7.00E-06	7	2.28E-01	Stokes-Cs	1.49E-03	6.80E-04	1.024	0.010	1.2570	3.48E-12	3.48E-08	1.52E-04	7.58E-04	1.52E-03	3.33E-03	6.06E-03
Beginning of Cunningham Slip Region			See Kn -->					Kn>0.01								
	7.50E-06	7.5	2.45E-01	Stokes	1.70E-03	8.35E-04	1.023	0.009	1.2570	3.24E-12	3.24E-08	1.74E-04	8.68E-04	1.74E-03	3.82E-03	6.95E-03
	1.00E-05	10	3.26E-01	Stokes	3.01E-03	1.97E-03	1.017	0.007	1.2570	2.42E-12	2.42E-08	3.07E-04	1.53E-03	3.07E-03	6.75E-03	1.23E-02
	5.00E-05	50	1.63E+00	Stokes	7.43E-02	2.43E-01	1.003	0.001	1.2570	4.77E-13	4.77E-09	7.57E-03	3.79E-02	7.57E-02	1.67E-01	3.03E-01
	7.50E-05	75	2.45E+00	Stokes	1.67E-01	8.18E-01	1.002	0.001	1.2570	3.18E-13	3.18E-09	1.70E-02	8.51E-02	1.70E-01	3.74E-01	6.81E-01
	1.00E-04	100	3.26E+00	Stokes	2.97E-01	1.94	1.002	0.001	1.2570	2.38E-13	2.38E-09	3.02E-02	1.51E-01	3.02E-01	6.65E-01	1.21E+00
Beginning of Stokes' Law Region			K < 3.3			Re < 2										
	2.00E-04	200	6.53E+00	Intermediate	6.53E-01	8.53	1.001	0.000	1.2570	1.19E-13	1.19E-09	6.65E-02	3.33E-01	6.65E-01	1.46E+00	2.66E+00
	5.00E-04	500	1.63E+01	Intermediate	1.86E+00	60.60	1.000	0.000	1.2570	4.76E-14	4.76E-10	1.89E-01	9.46E-01	1.89E+00	4.16E+00	7.57E+00
	7.50E-04	750	2.45E+01	Intermediate	2.95E+00	144.32	1.000	0.000	1.2570	3.17E-14	3.17E-10	3.00E-01	1.50E+00	3.00E+00	6.61E+00	1.20E+01
	1.00E-03	1000	3.26E+01	Intermediate	4.09E+00	267.12	1.000	0.000	1.2570	2.38E-14	2.38E-10	4.17E-01	2.08E+00	4.17E+00	9.17E+00	1.67E+01
	1.25E-03	1250	4.08E+01	Intermediate	5.27E+00	430.61	1.000	0.000	1.2570	1.90E-14	1.90E-10	5.38E-01	2.69E+00	5.38E+00	1.18E+01	2.15E+01
	1.35E-03	1350	4.41E+01	Newton	5.76E+00	507.71	1.000	0.000	1.2570	1.76E-14	1.76E-10	5.87E-01	2.93E+00	5.87E+00	1.29E+01	2.35E+01
Beginning of Intermediate Region			K < 43.6													
End of Newton's Law Region			K > 43.6			Re > 500										
	2.00E-03	2000	6.53E+01	Newton	9.01E+00	1177.35	1.000	0.000	1.2570	1.19E-14	1.19E-10	9.19E-01	4.59E+00	9.19E+00	2.02E+01	3.67E+01
	2.50E-03	2500	8.16E+01	Newton	1.16E+01	1897.99	1.000	0.000	1.2570	9.51E-15	9.51E-11	1.18E+00	5.92E+00	1.18E+01	2.61E+01	4.74E+01
	3.00E-03	3000	9.79E+01	Newton	1.43E+01	2803.76	1.000	0.000	1.2570	7.93E-15	7.93E-11	1.46E+00	7.29E+00	1.46E+01	3.21E+01	5.83E+01
	4.00E-03	4000	1.31E+02	Newton	1.99E+01	5189.32	1.000	0.000	1.2570	5.94E-15	5.94E-11	2.02E+00	1.01E+01	2.02E+01	4.45E+01	8.10E+01

Table A2. Stopping Distance

Particle Size	Settling Velocity (m/s)	Relaxation Time (s)	Stopping Distance (5m/s)	Stopping Distance (10m/s)	Stopping Distance (22m/s)	Stopping Distance (60m/s)
0.068	5.44E-07	5.55E-08	2.77E-07	5.55E-07	1.22E-06	3.33E-06
7	1.49E-03	1.52E-04	7.58E-04	1.52E-03	3.33E-03	9.09E-03
100	0.297	0.030	0.151	0.302	0.665	1.814
750	2.95E+00	0.300	1.501	3.003	6.606	18.017
1350	5.757	0.587	2.934	5.869	12.911	35.212

Table A3. Human Ventilation Rate

Activity (Ref)		Resting	Under Load	Units
Minute Ventilation	VE =	6	90	L/min
→ CFM	Flow/min =	0.212	3.18	ft^3/min
→ CFH	Flow/Hour =	12.72	190.8	ft^3/hr
	# People =	50	5	#
→ Σ(CFH)	Total Flow Rate = Q =	636	954	ft^3/hr

Table A4. Human Ventilation Rate vs Room Size

Description	Volume (ft^3)	CFH1	CFH3	CFH5	CFH8	CFH15	CFH30	CFH50	CFH75
Tub Shower	100	7.86 hr	2.62 hr	1.57 hr	0.98 hr	0.52 hr	0.26 hr	0.16 hr	0.10 hr
Small Cubicle	200	15.72 hr	5.24 hr	3.14 hr	1.97 hr	1.05 hr	0.52 hr	0.31 hr	0.21 hr
Large Cubicle	500	39.31 hr	13.10 hr	7.86 hr	4.91 hr	2.62 hr	1.31 hr	0.79 hr	0.52 hr
Small Office	1000	78.62 hr	26.21 hr	15.72 hr	9.83 hr	5.24 hr	2.62 hr	1.57 hr	1.05 hr
Standard Office	1200	94.34 hr	31.45 hr	18.87 hr	11.79 hr	6.29 hr	3.14 hr	1.89 hr	1.26 hr
14x18x8	2000	157.23 hr	52.41 hr	31.45 hr	19.65 hr	10.48 hr	5.24 hr	3.14 hr	2.10 hr
10x10x10	10000	786.16 hr	262.05 hr	157.23 hr	98.27 hr	52.41 hr	26.21 hr	15.72 hr	10.48 hr
50x35x8	14000	1100.63 hr	366.88 hr	220.13 hr	137.58 hr	73.38 hr	36.69 hr	22.01 hr	14.68 hr

APPENDIX B – DEFINITIONS

Particle Size: The diameter in microns of a particle laden with corona virus. This discussion assumes a static particle size. The diameter of a liquid particle changes with evaporation. This discussion is based on the diameter of the particle at any given point in time. COVID-19 has a diameter of approximately 60–140 nm. Water molecules have a diameter of approximately 0.000275 µm.

Forced Convection: The movement of air induced by the addition of energy. A ceiling fan or air conditioner vent are the most common examples. Forced convection air flow has a higher velocity typically than natural convection in an indoor space. The relevance is that higher air flow will sustain larger particles and be more effective at removing a higher percentage of the particles. Air flow also determines the pathway of aerosol particles.

Natural Convection: The movement of air induced by differential temperatures. The ceiling, walls and floor all have different temperatures. Hot air is less dense than cold air. The different weights cause cold air to fall and hot air to rise, thereby creating a natural convection air current.

Gravity: The force imparted by the mass of the planet earth on the mass of the particle.

Lift: The force imparted by an air flow on the particle.

Airflow Pathway: The pathway traveled by a corona virus laden particle.

Average Daily Air: Adult humans inhale over 10,000 liters of air per day. Contained within Average Daily Air volume are somewhere between 100 billion and 10 trillion particles. Not all particles will reach the lungs. (Tsuda et al., 2013)

Particle Distance: The distance traveled by a coronavirus laden particle.

Droplet Cloud: A cloud of coronavirus laden particles that will eventually fall to the ground.

Droplet Cloud Corona Virus Mass: The mass of corona virus in a droplet cloud.

Aerosol: A very small, airborne particle governed by Stokes' Law or Stokes' Law with a Cunningham Slip correction factor. (<1350 microns)

Aerosol Cloud: A cloud of coronavirus laden aerosol particles that will travel with the airflow pathway.

Aerosol Cloud Coronavirus Mass: The mass of coronavirus in an aerosol cloud.

Fomite Transmission: Occurs when an intermediate inanimate object transmits the virus from one to another.

Indirect Transmission: Airborne droplets enter the respiratory system of a susceptible individual. Aerosol-based transmission is a form of Indirect Transmission.

Particle Transport: The transport properties of a particle are characterized by the particle's interaction with surrounding molecules. The size of an aerosol particle is the fundamental characteristic that determines its transport properties. The size is the germane characteristic for interaction of aerosol particles in air.

Sedimentation or Settling Velocity: How fast the particle will fall to the ground. Sometimes referred to as Particle Settling/ Terminal Velocity in a fluid. Forces due to Drag/lift = Inertial force/gravitational force

Relaxation Time: Time required for a particle to transition from initial velocity to settling velocity.

Stopping Distance: Distance for a particle with horizontal velocity to reach zero due to external forces. Distance covered during the relaxation time.

Micron: 1×10^{-6} Meters = 1 Micrometer (µm)

General Flow: Describes the motion of molecules through a medium relative to one another. Determining flow pattern is complicated, but we may use sets of relations to describe the flow. (K, Kn, Re)

Reynolds Number: Term derived to describe air resistance of arbitrarily shaped objects in an air stream.

Knudsen Number: Ratio of the mean free path to particle diameter.

When Kn is high, the particle is smaller than the free path and will collide less frequently with other particles.

When Kn is low, the particle is larger than the mean free path and will push nearby molecules as it travels.

The Knudsen number can be used to determine the degree of slip or rarefaction of a particle in flow [3]:

- { Kn <0.01} : Laminar flow (Stokes Flow)
- {0.01< Kn <0.1} : Slip flow (Stokes with C_s)
- {0.1< Kn <10} : High Slip Transitional
- { Kn >10} : Diffusion, Free-molecular flow [4]

Boltzmann Constant: The Boltzmann constant (kB) relates temperature to energy. The total kinetic energy (E) in joules is related to temperature (T) in kelvins according to the nist-equation E = kBT.

Brownian Motion: Describes diffusion and the motion of particles in Free-molecular flow.
Applies to very small particles, molecules and atoms. Angstroms or Nanometers