Report to the Building Re-opening sub-committee
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Singing, Covid, Aerosols, Fluid Mechanics, and First Church

Summary

Many conflicting and at times sensational headlines have circulated regarding singing and the potential spread of COVID-19. This has been magnified by recent media accounts describing selected conclusions from some (non-peer reviewed) fluid mechanics work from Germany. This report provides background material related to accounts on the mechanisms for the spread of COVID-19, and, an assessment of the German work from someone with a fluid mechanics education and decades of fluid mechanics work experience (but, no virological experience). While it is certain that COVID-19 can be spread by exhaled "droplets" (large droplets that settle quickly), there is a growing amount of evidence to support the hypothesis that COVID-19 can also be spread by exhaled "aerosols" (small droplets that remain suspended in the air and are spread by air movement). The dangers from these aerosols are believed to be mitigated by the widespread use of appropriate PPE and masks, but, that is not always practical, especially when singing is involved. Initial media reports [1, 2] claiming that the German work proves that singing is safe, fail to also include the discussion and conclusion from that work [5] that stresses the importance of fresh air ventilation. Fluid mechanics studies have shown the importance of having sufficient fresh air ventilation in the vicinity of a person infected by a disease that can be spread via exhaled aerosols, to protect uninfected individuals in the same room. This presents a challenge for The First Presbyterian Church in Philadelphia because, for energy conservation reasons, many of the natural ventilation features of the original building have been permanently sealed. Extension of any conclusions from this report to other locations should be cautioned, as each individual facility will need to be assessed based on its own specific circumstances.

Media

Lots of conflicting and sensational headlines have been "published" related to the spread of COVID-19. This is made even more confusing by the proliferation of internet blogs, and, by the almost instantaneous spread of the most sensational headlines via social media. For example, one internet blog which was shared multiple times on Facebook [1] was titled:

Singing Is Unlikely to Spread COVID-19

Meanwhile, five days later, The Guardian carried the following [2]:

Did Singing Together Spread Coronavirus to Four Choirs?

While six weeks earlier the LA Times carried [3] the sensational:

A choir decided to go ahead with rehearsal. Now dozens of members have COVID-19 and two are dead.

Many of these stories focus on specific facts from specific events, and occasionally also refer to technical articles in peer reviewed technical journals. However, often quotes from those technical journals do not tell the complete story and important aspects of the research are not included in the simplified and summarized synopses.

Why this Report?

A number of recent reports [e.g. 1, 4, 5] have described how fluid mechanics studies have been used to argue that singing is very unlikely to be a significant cause of the spread of COVID-19. This is in stark contrast to some choral organizations (e.g. Sweet Adelines International [6]) which cancelled all competitions for 2020. Since my PhD and one of my Masters were focussed

on fluid mechanics, and, much of my working career has included understanding of fluid mechanics applications, I felt well qualified to dig into the various technical papers and media reports. This was done to understand how the fluid mechanics research was performed, and, to assess whether the reported media conclusions from that work were consistent with other available technical information related to COVID-19. In addition, as a multi-term past president of the Board of Trustees, and as an elder of The First Presbyterian Church in Philadelphia, I felt an obligation to utilize my professional background to help the leadership of our church better understand the various conflicting reports, at least as their conclusions related to fluid mechanics studies.

Since I do not have any virology background, this report will describe conclusions of others, but, will not make any speculation about the actual viability of any viruses which may be contained in droplets and aerosols.

Cases

By now, most people have heard of the choir incident [3] involving the Skagit Valley Chorale when it rehearsed at the Mount Vernon Presbyterian Church in Washington state. A more detailed scientific investigation of this event was shared by the CDC [7]. This is by no means the only incident involving choirs and/or churches. The Guardian [2] describes four different choir events that have been circumstantially linked to Covid spread. A recent LA Times article [8] describes a number of California incidents where church services, some with minimal attendance but proceeding for the purposes of live-streaming, are believed to be locations where virus spreading occurred. Newsweek [9] reported on two southern US churches, which reopened, and have since re-closed following the death of the pastor and illness of several leaders in one of those churches, and reported spread of the virus in the other. CTV News from Canada [10] reported on suggestions that the spread of Covid in churches may be due to singing.

Churches and choirs are not the only locations where spreading of the virus has been reported and subsequently investigated. Reference 11 describes a number of incidents, including:

- Restaurant: Patrons at a restaurant who were “down wind” of an asymptomatic COVID-19 carrier were infected, presumably from the virus being carried by the movement of air in the restaurant by the air conditioning. Patrons not in the flow path did not contract the virus.
- Work Location: Many workers on the same floor, and once again down wind of a subsequent positive individual contracted COVID-19, while those on the other side of the building on the same floor remained negative.
- Curling: A contestant at a curling event in Canada appears to have caused the spread of COVID-19 amongst both other competitors and spectators.

Droplet versus Aerosol Transmission

During human activities, like breathing, talking, singing, coughing, and sneezing, droplets are emitted from the mouth and/or nose. There is a wide distribution of sizes that are generated during these activities. Two terms are frequently used, based on the seminal work of Wells [12], where droplets larger than 5 microns (1 micron is 1/1000th of a millimeter, a typical human hair is about 50 -100 microns) in size are referred to as “droplets”, whereas droplets smaller than 5 microns are referred to as “aerosols”. The importance of the difference between the two is that in general, “droplets” will fall to the ground in the vicinity of where they were generated, whereas “aerosols” can remain in the air for seconds, minutes, or even hours, depending on their size and prevailing conditions.

In the early period of this pandemic, the World Health Organization [13] concluded that the primary means of COVID-19 transmission was via “droplets”. This is consistent with many of the reported recommended precautions, as these droplets would settle close to their point of generation, and could subsequently be touched by others. There appears to be little doubt that droplets are one of the most important means by which COVID-19 spreads.

There is much disagreement as to the importance of aerosols in the spread of COVID-19, especially from normal human activity. Dangerous aerosols are generated from certain medical procedures [13], thus requiring hospital staff performing those procedures to wear very specific PPE. However, the same report [13] discounts the role of aerosols from normal human activity in the spread of COVID-19. In contrast, there are many reports [11, 14, 15, 16, 17, 18, 19, 20, 21] that suggest that COVID-19 is most probably transmitted by airborne aerosols. Reference 14 and 19 in particular provide thorough, but easily readable discussions of the various transmission routes, and both conclude that aerosol transmission is likely. What is abundantly clear is that normal human activities like talking and breathing generates a wide range of sizes, and, that the smallest ones of these can remain airborne for hours.

The CDC [22, 23] refers to respiratory droplet transmission, but, does not rule out transmission by associated aerosols. They mention that an infected person can spread the virus by talking, and subsequent inhalation by a nearby person. As discussed in reference 20, this form of infection is not traditionally used with reference to “droplets”, but instead, is usually reserved for “aerosols”. This reference [20] also quotes the Chinese Center for Disease Control and Prevention, as saying that COVID-19 transmission occurs primarily by respiratory droplets and close contact, with the "possibility of aerosol transmission in a relatively closed environment for a long time exposure to high concentrations of aerosols."

One issue that is hotly debated within the scientific community is whether the virus remains viable and infectious in aerosol form. Most discussion on this topic refers to reference 24, which concludes:

… the virus can remain viable and infectious in aerosols for hours …

This is supported by a recent study from China [25] where active virus was detected in the air up to 4 meters away from patients.

However, because the droplets studied in reference 24 were generated by mechanical means into a humid chamber, some researchers discount their conclusion for virus viability in human activity generated aerosols [e.g. 5, 13] into normal environments. Clearly, much more research is needed on this topic.

Droplet Size, Generation Mechanisms, and Singing

Over the years, many studies have looked into the various mechanisms of droplet formation in the respiratory system [e.g. 26, 27, 28]. Any air passing through the respiratory tract will create droplets [14]. Reference 27 studied the size distributions from various activities like coughing and talking, and details phenomenological droplet formation mechanisms in various locations in the respiratory system. The smallest droplets are formed during inhalation, when small liquid filled passages fill with air and expand, resulting in a “fluid-film bursting” formation mechanism [27]. These droplets are subsequently carried out by the air as the person exhales. Droplets are also formed in the larynx as air flows over the fluid covered vocal cords, however, these droplets, in general, are larger than those formed deep in the lungs [27], and will often be too large to become an aerosol, and subsequently settle quickly in the vicinity of the person.

Singing is believed to cause a problem, especially for respiratory system diseases [29]. There are believed to be two different reasons for this. As described above [27], the fluid film bursting mechanism produces very small droplets during inhalation. Rapid inhalation, as a professional singer is trained to do, is believed to magnify this mechanism. This is then amplified, because, as pointed out in reference 30:

A good singer knows how to use all the air in their lungs

This ensures that all of those newly formed droplets are exhaled into the air around the singer.

When droplets are inhaled, the largest ones collide with the walls of the throat, releasing the virus in the upper respiratory system. However, the very smallest aerosol droplets are carried by the inhaled air deeply into the lungs before they are absorbed [21]. This means that not only can singing cause an increase in aerosol size droplet formation due to the necessary controlled inhalation and fluid-film bursting mechanism, near-by COVID-19 free singers can subsequently breath these virus laden aerosols deep into the lungs during breaths between refrains.

Bromage [11] suggests that:

Successful Infection = Exposure to Virus x Time

This formula explains why so many of our health care workers have been infected by COVID-19. It also is consistent with the apparent number of infections which have been associated with singing.

There is another phenomena that has been reported in the literature, an individual SuperSpreader, and Super Spreading Events [27, 31]. It is well known that some individuals produce far more droplets during breathing, talking, and singing, than others. These individuals are often referred to as SuperSpreaders and are believed to be disproportionately responsible for outbreaks of airborne infectious diseases. There is no clear way of identifying these individuals. SuperSpreader Events (SSE) are the subject of reference 31, where detailed analyses are presented for 54 SSEs which occurred in 28 different countries. Many of those 54 events involved either singing or religious services.

On a recent American Choral Directors Association COVID-19 webinar, Prof. Milton [21] described in detail aerosol related COVID-19 transmission issues related to singing. Many of the issues mentioned above are discussed in detail in his presentation.

German Fluid Mechanics Studies

Professor Kähler and coworkers have made available two Covid related (non-peer reviewed) reports [4, 5] on their institution's web site, that have received widespread media attention [e.g. 1, 2]. These reports have focussed on the use of fluid mechanics to reach conclusions about mechanisms related to the spread of COVID-19. However, there are some basic assumptions in their analysis that put some of their media reported conclusions in doubt.

In their first study [4], they report droplet settling rates, and water evaporation rates, from droplets of various sizes. They conclude, consistent with the original WHO guidance, that only large droplets can result in the transmission of Covid between people. They correctly show how the settling rate increases with droplet size. But, in reaching their conclusions, they ignore the fact that the decreasing droplet size (due to evaporation) decreases the settling rate. Also, as water evaporates, the resistance to mass transfer within the droplet will increase, causing the evaporation rate to drop further. While they state that complete evaporation of water would make any virus non-viable, the articles mentioned earlier when discussing aerosols, cast a level of doubt on that conclusion. If aerosols are one of the transfer mechanisms of COVID-19, either

their calculated evaporation rates are incorrect, or, their conclusion about non-viability of the dried droplet containing the virus is incorrect.

In their first report [4], they also overlook the possible impact of convective spread of droplets in a room. Convective transport is the movement of droplets and aerosols by movement in currents of air. Upward movement of air can negate the downward settling due to gravity, and cause the droplets and aerosols to remain airborne for longer than simple gravity settling would suggest. They also assume that the only horizontal movement of droplets can be due to the air that is being exhaled, which, does not extend far beyond the mouth (or nose). They report similar findings in their second report [5] where they explicitly studied singing and musical instruments. Their initial conclusions, which ignore the impact of convection, are what has been reported in the media. In their second report [5], they do also include a discussion about convective movement and distribution of droplets. This leads the Germans to also discuss the less-well media reported importance of appropriate fresh air ventilation. In addition to the media reported conclusions, they also conclude that effective ventilation is critical to ensure safety. Convective movement of infectious droplets and aerosols is also discussed in detail in references 31 and 33, which describe how convection can be caused by many different phenomena.

Of course, there is an alternate solution that the German studies [4, 5], and many others, recommend - the widespread use of appropriate masks and PPE.

Importance of Fresh Air Ventilation

While the media reported [1] conclusions from the second German Fluid Mechanics study [5] emphasize the “safety” of singing with reasonable distancing, it does not also include one of the conclusions from their study, that being [5]:

*… **it is also very important to ensure that the room is sufficiently large, well ventilated and provided with sufficient fresh air. The automatic fresh air supply should be significantly increased compared to the legal requirements in order to keep the virus load in the room low. An open window cannot replace a high-quality automated fresh air supply**.*

This is consistent with CDC guidance [32] for faith based organizations. This guidance includes the following recommendations:

*… **Ensure that ventilation systems operate properly and increase circulation of outdoor air as much as possible by opening windows and doors, using fans, etc. Do not open windows and doors if they pose a safety risk to children using the facility**.*

In the body of the second German study write-up [5], they say:

*… **Poor ventilation could cause people in the immediate vicinity to become infected and a fan would be able to infect people in the wake of an infected person**…*

From that same report [5], below are the sections specifically discussing ventilation and convection:

*…**4.5 Ventilation***

In addition to adhering to the rules of distance and placement recommendations, it is also very important to ensure good and proper ventilation in the rehearsal rooms in order to minimize the risk of infection from slow room air motions. To ensure this, on the one hand the air exchange rate should be significantly increased in times of a pandemic, on the other hand, with ideal room ventilation, the air should be supplied from below through the floor and be extracted flatly via the ceiling. Sideways air removal can cause

the air contaminated with viruses to flow to non-infected persons, which may lead to infection even over longer distances in streamwise direction under unfavourable conditions. For this reason, fans in the rehearse room are also not recommended if they transport the air at low speed (less than 0.3 m/s) from person to person. With increasing speed, this danger is reduced because the exhaled air volume is diluted by a cross-flow, and strongly turbulent flow motions, thus reducing the viral load, but speeds greater than 0.3 m/s are perceived as unpleasant.

4.6 Convection

There is another point to consider: An ascending convection flow usually forms around and above the warm bodies of people, as the air heated by the skin and the air exhaled is lighter than the air in the surrounding area. This effect also speaks in favour of extracting the room air through the ceiling.

Without doubt, the overwhelming conclusions from multiple sources all agree that good fresh air ventilation is essential, when considering the safety of people in the vicinity of anyone singing who may be infected by COVID-19.

Following the release of their second report [5], I have had email discussions with Professor Kähler. In one of his emails, he explained how he had given a release for a big band and choir to perform in Germany because "***All my recommendations could be followed***", (which presumably includes ventilation described above).

The need for the types of ventilation described above can be simply mitigated by the widespread use of appropriate masks and PPE.

Implications for First Church

During one of my terms as President of the Board of Trustees, AOS was retained to perform a review of the church building and facilities, for the purposes of developing a job list that eventually formed the basis for the Preserving First project. One feature that they were explicitly asked to include in that assessment was the possibility of adding air conditioning, or, some other low cost option, for cooling the sanctuary in summer. A number of members of the Taskforce were curious, because when the church was designed, hot humid summers existed in Philadelphia, and we wondered why the building did not have better summer ventilation. AOS identified a number of modifications that had been made over the 150+ years since the church was designed, which eliminated most of the originally designed summer ventilation features. The two most obvious ones were 1) the bricking over of ventilation running along the east side of the basement, and 2) the closing off of ventilation windows on the north end of the church, believed to have occurred at the time of an organ expansion. Both of these modifications would have resulted in substantial savings in heating costs in winter, but, also significantly reduced the fresh air flow through the church.

It is our common practice, in summer, to utilize fans to circulate air in the sanctuary, and opening of the windows in the ceiling. If COVID-19 aerosol droplets were exhaled into the sanctuary air, the use of the fans is likely to ensure that most congregants would experience the opportunity to inhale this infected aerosol. The ceiling windows are very small, compared to the volume of the sanctuary, and while they may result in some cross ventilation in the layers of air in the upper heights of the sanctuary, they are insufficient to provide significant ventilation of the bulk of the sanctuary. Attempts to increase the flow of external air flow, even on windy days, by opening the front and narthex doors has minimal impact on air in the sanctuary because there is no significant openings to permit the cross flow of air. There are no sizable openings to the outside on the east, south, or west sides of the sanctuary to permit crossflow. This means that any aerosol exhaled into the sanctuary is likely to remain in the sanctuary and eventually settle out on the floor and fixtures (where they could be cleaned using regular cleaning procedures).

On a very hot summer Sunday, we have moved our 11am service into Old Buttonwood hall. Although this is in air conditioned comfort, the air is primarily circulated through the air-conditioning system, with very little exchange with fresh air. This would mean that the concentration of any COVID-19 containing aerosols would slowly build up while any infected congregants were present. Once again, this aerosol would eventually settle out, and could be cleaned using normal cleaning procedures.

In winter, the sanctuary is heated by the blowing of heated air up through floor registers, one of Kähler's recommendations. If one assumed that any infectious aerosol was deactivated during the air heating process, then, in principle, it would be safe to stand over these floor registers. However, the return registers, unlike Kähler's recommendations, are in the floor, and not the ceiling. This sets up air movement patterns in the sanctuary, which again, would have the undesirable tendency to distribute any exhaled infectious aerosols broadly throughout the entire congregation.

In discussing our building with Professor Kähler in my email exchanges, he agreed with my concerns related to our poor fresh air ventilation into our building. While admitting that he has no first hand knowledge of our facilities, and, without having performed a detailed study, he said,

"***surely measures for forced ventilation are necessary.***"

He went on to add, when we were discussing choir singing,

"…***if there are many elderly people with pre-existing conditions in the choir, then I think it would be better to refrain from singing in closed rooms for the time being.***"

Note that while his comment describes the safety of the choir, it also equally applies to other in the same space, and for First Church in particular, includes the clergy leading the service at the lecture and pulpit, and the playing organist.

His closing suggestion was:

"***Maybe there is a possibility to prolong the singing outside during the summer.***"

Conclusions

While it is certain that COVID-19 can be spread by exhaled "droplets", there is a growing amount of evidence to support the hypothesis that COVID-19 can also be spread by exhaled aerosols. The dangers from these aerosols are believed to be mitigated by the widespread use of appropriate PPE and masks, but, that is not always practical, especially when singing is involved. Fluid mechanics studies have shown the importance of having sufficient fresh air ventilation in the vicinity of a person infected by a disease that can be spread via exhaled aerosols, to protect uninfected individuals in the same room. This presents a challenge for First Church because, for energy conservation reasons, many of the natural ventilation features of the original building have been permanently sealed.

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