If Music be the Food of Love, Sing On, Sing On, But How?



Guidance on tackling Covid-19 places restrictions on group gatherings, so how can bands and orchestras continue to play music safely together? Peter Ladkin analyses the prevailing droplet-focussed guidelines for musicians and questions whether aerosol dispersion risks have been properly addressed.

Three weeks ago, at the farm store, I bumped into a neighbour who plays bass clarinet with the Bielefeld Philharmonic orchestra ("Bielefelder Philharmoniker" in German: Bielefelders who love harmony. We do). We often talk about breathing technique and mental attitude, her expertise, but now we talk about my speciality, safety, too. Playing musical instruments, especially wind instruments, or singing, together with others in an enclosed space, is as of early 2020 no longer safe.

Communal music making is one of the most rewarding experiences many people have. Besides the professionals, we have in my city of 330,000 over a dozen amateur choirs and orchestras, as well as large numbers of bands such as mine. What to do? Make it safe again. This interdisciplinary endeavour involves studies of human anatomy and physiological behaviour, fluid dynamics, ventilation and germicidal engineering. Here is a guide to answering the title question.

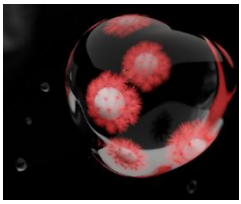
When the music stopped



All public events were cancelled in Bielefeld from 15th March 2020. The city theatre company encompasses opera, musical theatre and spoken theatre, as well as the Philharmoniker. There is a YouTube video series on their channel Theater Bielefeld called Gemeinsame Sache, "[making] common cause". The series features solo performances – readings, dance, music – in various Bielefeld cafes and shops, which were at that time also all closed. Here is my neighbour, Margarete Fiedler, playing a folk tune in classical style on this lovely instrument [1], in the Kachelhaus café – a building covered in white and light-green glazed tiles, called "Kachel".

Margarete told me at the farm store that the Philharmoniker had just commenced again with performances, with a reduced contingent and of course a widely-spaced audience. The orchestra pit in the city theatre has been approved to accommodate 10 musicians. The engineer in me wonders how they got to that number. The theatre was renovated a few years ago to the design of a company called theapro, and there are some photographs in a diorama on their website [2] as well as a geometric floorplan (published without a scale, but some dimensions are given). The Philharmoniker and I are aware that the Institute for Music Medicine (IMM) at the University of Music in Freiburg has published indicators for distancing and other parameters of dealing with Covid-19 for musicians, based on the existing literature as well as some local experiments.

Distancing guidance – for droplets



I read the first version of the IMM guidance (in German and English) when it was first published in April 2020 [3]. It is now available in seven languages, including English [4]. It concerns the Covid-19 risk assessment of the activities of playing and teaching music and singing. I'll refer to the authors and report collectively as IMM. The assessment was updated four times until 17th July 2020, so there have been five versions. Other documents on guidance for musical activities refer to it, such as that of Public Health Ontario [5] and Swalje and Hoffman [6].

The flute family consists of transverse flutes, as well as recorders and other fipple flutes, and there is a Japanese flute which is blown in the same configuration as a fipple flute, that is, held parallel to the air stream, but with a transverse edge without a fipple, but it is not used (much) in Western music. The IMM regards flutes as particularly problematic, because much of the air expelled in playing is not necessarily contained within the instrument (a fair amount is, in experienced players, but less so with beginners). Based on preliminary experiments with symphonic players from Bamberg, as well as considerations derived from the vocal-fluid-dynamic literature, the April edition of the IMM guidance was recommending distancing of 3-5m in the blowing direction for flute players and 1.5m transversely. The document updated on 17th July 2020 relates some experiments in which disturbance of the air around wind-instrument players was measured. Essentially no disturbance was found at 2m distance from flautists and singers. IMM thus revised its advice to 2m radial minimum distancing for all musicians (including singers). This advice addresses the issue of droplets which fall to the ground under gravity.

Something in the air

The issue of aerosols is different, however, and must also be addressed. The distinction is made qualitatively, droplets being those particles which fall to the ground under gravity, and aerosols those smaller particles which remain suspended in the air. For convenience, the distinction is set at a reference level, arbitrary but realistic, of 5μm (droplets greater than, aerosols smaller). While droplets were generally the main concern as aerial vehicles of Covid-19 transmission in March and April 2020, largely it turns out for reasons of tradition, possible Covid-19 transmission through aerosols has been a scientific concern of late.

Aerosols can remain suspended in air in an enclosed space for a number of hours. Mürbe et al say three hours viability for SARS-CoV-2 [7, p4], citing van Doremalen et al [8]. Wendy Barclay, a British virologist and member of SAGE, suggested a practical one-hour viability in a BBC television interview in July 2020 [9].

"Aerosols can remain suspended in air in an enclosed space for a number of hours"

If we assume aerosols containing viable virus accumulate at a fixed rate, then as a first approximation the amount of aerosol in the air at a specific time follows a linear progression to a stable state, as follows. Assume viable virions in aerosol (vva) accumulate at a rate of V per unit time. Start at Time 0 with 0 vva. At 1 time period, there are V vva; at 2 time periods there are $(V + V)$ vva; ….. at n periods there are $V \times n$ vva. At some point those virions become unviable; let us assume after T time units. Call T the vva persistence. At 0 time, there are no aerosols; at T time units, the persistence limit of the initial V units expelled between time 0 and 1 has been reached, and they will all become unviable up to time $(T + 1)$, but V new vva will have been added also between T and $T + 1$, so the vva present at $T + 1$ is the same number as were present at T. A stable vva count is therefore reached at time T, and that will be $V \times T$. Obviously, this is a discrete approximation of a continuous process. Does it yield an accurate result?

A better approximation might be to take 1 time unit equal to the half-life of vva accumulations. Van Doremalen et al found this to be around an hour [8, Figure 1]. Let us take V to be the number of expelled vva that survive at 1 time period. As before, at time 0 there are 0 vva; at time 1, V vva; at time 2, $(V + ½ V)$, since only half the vva from the preceding time period are still viable, and there are V new vva.
At time 3, there are $V + ½ (V + ½ V)$; and so on. We have the recurrence relation:

- $a_0 = 0$;
- $a_n = ½ a_{n-1} + V$ for $n > 0$

which has the general solution $a_n = V \times (2^n - 1)/2^{n-1}$ which obviously converges to $2V$ in the limit, from below. The maximum concentration attained in the room is therefore a little below twice the amount of vva accumulated during a half-life period. By twice the half-life period it is only one and a half times V, but by three or four times the half-life period it is pretty close to twice V.

Estimating the steady-state vva in the space by the first method, with persistence at three hours, leads to steady-state accumulation of $3 \times V$. The second estimation with half-life of one hour leads to an accumulation approaching $2 \times V$ from below, which is already

somewhat better. We shall see below that IMM says that an air exchange of 6 times room volume per hour (or a 10m ceiling!) yields "sufficient" removal of aerosols, and, failing that, thorough room ventilation every 15 minutes. If V is the accumulated vva per hour, extrapolating linearly we estimate maximum vva accumulation to be $\frac{1}{6}V$, respectively $\frac{1}{4}V$, which is a twelfth, respectively an eighth, of the steady-state unventilated accumulation. But they are both still multiples of V. So if V is, say, more than 6 times an infectious dose, even following IMM air-exchange guidelines you still have an infectious accumulation in the room. Looking at it this simple way, having seven infectious people in the room might be problematic for others even if you ventilate often! But the length of time of exposure also seems to play a critical role in transmission of Covid-19; the 15-minute guideline was also used in the definition of "close contact" in initial general advice about infection opportunities in February and March 2020.

What is an infectious vva concentration? No one yet knows what it takes in viable-virion intake to become infected, as noted by Germany's "superstar" virologist, Christian Drosten, in a recent interview [10]. It is implausible that there would be just one "magic" number – people likely differ as to their susceptibility to infection, and it does depend on how the virus can enter into your body – but a reference value would be helpful. There isn't one.

A refreshing approach to decontamination

If one is refreshing, respectively decontaminating, air constantly, then stable levels of virion and thus persistence and accumulation do not matter as long as the refresh/decontamination rate is lower than the persistence as well as low enough to keep current aerosols at a non-infectious level.

Bahl et al reviewed the propagation of breath-expelled aerosols and droplets in general [11] (note that the paper was submitted on 26th Feb 2020, so relatively early on in the progression of Covid-19). It includes recent work of Lydia Bourouiba's MIT Laboratory [12]. Bahl et al noted that most of the more recent papers report droplet ranges of over 2m, depending on the size of the droplets – 16µm droplets were reported to travel up to 7m, and Bourouiba reported just short of 8m range for all droplet sizes. The scientific issue with all these experiments is the accurate detection of smaller droplets during experiments.

"What might not have been an infectious concentration at first could turn into one during accumulation"

Aerosols remaining in suspension in air in enclosed spaces used for musical activity thus pose a problem. They accumulate, to a limit, and what might not have been an infectious concentration at first could turn into one during accumulation. IMM recommends conducting musical activities outside, under distancing, where possible, since the threat from aerosols in the open air is thought to be negligible. When inside an enclosed space (room, hall) IMM says that the size of the room, the number of people present, and the length of time spent in the room all seem to play a role, and reference a 2006 review of aerosol transmission of influenza B virus [13].

A recent addition to the IMM document says "*from an air exchange rate of 6/h on, a sufficient removal of aerosols can be assumed*" [4, p16]. "6/h" means 6 times room volume per hour, which I shall write as 6 Rvol/hr. The authors mean a replacement with air from outside the room space, assumed to be pathogen-poor. I summarise the IMM general recommendations as follows:

- as much space as possible ("*cathedral situation*"); they speak of a ceiling height of 10m or more being comparable to an air exchange of 6 Rvol/hr [4, p16];
- when possible, air exchange of at least 6 Rvol/hr [4, p16]
- if this air exchange rate is not available, thorough indoor ventilation (without occupants) of smaller spaces every 15 minutes, or using rooms with an HVAC system (presumably there are some requirements for the HVAC system, but these are not specified); this amounts to 4 Rvol/hr, although such replacement will not be as perfect as this arithmetic implies
- assessment of CO_2 amounts, via a CO_2 "traffic light" based on the Pettenkofer number (1000ppm), since the quantity of CO_2 is dependent on outbreathed air, which is where aerosols (in whatever concentration) originate also. So, when the light goes red (>1000ppm), evacuate and ventilate.

There are two issues which I see arising from this advice.

First, 6 Rvol/hr is regarded as in any event sufficient, however "ventilation" every 15 minutes, which amounts to 4 Rvol/hr (if perfect), is regarded as adequate. Those are two different amounts. Is 4 Rvol/hr adequate or not? If so, the 6 Rvol/hr figure is superfluous. If not, the "ventilation" requirement should surely be raised to "every 10 minutes" to maintain consistency.

Second, it is not clear to me why it should be that the Pettenkofer number itself is key. Obviously it is key from the point of view of CO_2, and the authors are assuming that V is related linearly to CO_2 exhalation, which seems reasonable. But, as noted above, nobody knows what the not-infectious/infectious vva limit is. Why should it coincide with the Pettenkofer number?

The guidance in practice

What are the practical consequences of this guidance?

My music space is sparsely furnished, somewhat over 7m in length and 3.5m in width, with an average ceiling height of about 2.75m, which makes it just short of 80m^3 in volume. Using the previous IMM figure of 5m in front of flutes, we have played during rainy weather indoors with three flutes (one transverse, two fipple) in three of the four corners, with open windows to the outside near all players and a good draft coming through. That fits the original IMM guidance, but is difficult when the weather is cold.

Under the latest IMM guidelines of 2m radial distancing I could likely manage to configure 4-5 players geometrically, good enough for chamber music and small traditional-music sessions, but not for my 6-singer choral group (maybe one of us can sing in the corridor outside, like Harry Secombe in the Ying Tong song [14]). However, winter will make ventilation problematic. Breaking every 15 minutes for ventilation might work for professionals, but will likely put off amateurs having or trying to have fun. Which brings us to filtering, ventilation and disinfectant devices.

Germicidal irradiation

Let us start with ultraviolet germicidal irradiation, UVGI. There are various UVGI devices on the market, in the UV-C band, which is most effective in destroying RNA/DNA of microorganisms – as well as damaging human eyes. Such devices can be installed inside existing HVAC systems moving building air, but if you don't have one (most older houses,

like mine, do not) then you could consider a standalone or wall-mounted device. Such devices suck room air into a tube enclosing a UV-C lamp and evacuate it out the other end. No UV-C radiation makes it outside the tube.

For microbe disinfection, including viruses, the most effective wavelength is said to be 260-265nm (the DNA absorption peak). Mercury vapor lamps produce 95% of their energy at 253.7nm, which is regarded as effective germicide [15, p18, esp. Figure 2.1]. Mercury is of course highly poisonous, and thus requires careful handling (don't drop that lamp!). There are said to be LED variants but I haven't found any. I looked for such devices in stand-alone variants, considering only those for which relatively detailed performance parameters are publicly available. The least expensive sells for around €500, and achieves nominally 80m^3 per hour throughput. The most powerful standalone device I found achieves nominally 300m^3 per hour throughput, and costs over ten times as much at €5,200 wholesale (retail, add €1,000-2,000). So the inexpensive device achieves a circulation rate of 1 Rvol/hr in my music room, and the most expensive 3.75 Rvol/hr, both short of the rate of 6 Rvol/hr highlighted by IMM, but the higher-performance device does almost attain the "ventilation" requirement of 4 Rvol/hr. Since these devices only experience flow resistance internally, one could expect actual throughput performance to be close to nominal. The noise the devices make when operating is relevant, but the levels seem acceptable at around 30dB per device. So it is possible, although expensive, for me to achieve appropriate levels of clean air/replacement air through UVGI devices on the market.

Another option for non-ventilated rooms is an "upper room system", which UV-irradiates the upper part of a room, above the people, during use. The idea is that air containing aerosols emanates from people and is warmer than the ambient, thus rising into the upper part of a room, where it is then disinfected by the UV-C radiation. Additional circulation mechanisms might be required: "*[g]ood air mixing is necessary*" for effectiveness; "*[w]hen rooms lack adequate air movement, the addition of mixing fans is a satisfactory solution*" [15, Chapter 9]. Such systems have been in use "*for decades, and data that has accrued from installations in hospitals, schools, army barracks, and other indoor environments has shown them to be predictably effective provided the systems are properly designed and appropriate safety precautions are taken*." [15, Chapter 9].

One of the main safety issues with upper-room systems is the level of reflected UV-C radiation which arrives where the people are. UV-absorbing paints are available, which can help. Kowalski cautions about use of such systems where floor-to-ceiling heights are lower than 2.3m, because of the hazard of eye exposure. Mine is 2.70m, resp. 2.78m. It does seem as if significant room-preparation is likely to be necessary, as well as testing – "*[i]nvariably, photosensor measurements will be taken to establish that no hazardous levels of UV exist below the UV zone in the habitable areas*" [15, Chapter 9].

How much irradiation do aerosols need to ensure adequate SARS-CoV-2 virion destruction? One speaks of log 1 (90%), log 2 (99%), log 3 (99.9%) and log 4 (99.99%) levels of disinfection. Hessling et al surveyed current knowledge concerning UV-C and coronavirus inactivation in May 2020 [16]. The authors conclude "*To date, UVC radiation has been effective against all coronaviruses in all published investigations, although the absorption properties of the sample media reduced inactivation success. The calculated upper limit for the log-reduction median dose (in low-absorbance media) is 10.6 mJ/cm^2, but the probably more precise estimation is 3.7 mJ/cm^2.*"

Heilingloh et al achieved complete inactivation of SARS-CoV-2 at a concentration of 5×10^6 $TCID_{50}$/mL with a dose of 1048 mJ/cm^2 [17], about 100 times the log-reduction median dose reported by Hessling et al.

How much aerosol is emitted by singers or flute players? For this, we would turn to the results of the PERFORM project, led by the chemist Jonathan Reid and singer/surgeon Declan Costello [18]. The relative difference in emissions between speaking and singing is a factor of 1.5-3.4, which, while statistically significant, is not the real driver. That comes with the volume of the activity. Higher-decibel activity is associated with 20-30 times the emissions of quieter activity. As far as I know, results on instrument playing are not yet available.

Gregson et al [18] emphasise the relative quantity of emission. Since vva levels for infection are not known, it is not known how much virus in emissions from speaking/singing leads (with varying probability) to infection. It follows that the amount of irradiation to which room air should be exposed over what period of time, in order to eliminate an infectious concentration of aerosols, has not yet been established. Heilingloh et al's results concern exceptionally strong concentrations of virus in liquid preparation, which will attenuate the UV some, on a dish. Aerosols will afford nowhere near that concentration, and become more or less dry in quite a short time, so there will be no attenuation through liquid.

Filtration

Now to HEPA air filtration devices. They are commercially available, also stand-alone, filter out particles down to 3µm, but can be loud. It requires a lot of work to push-pull the air through the dense filter elements , and some of that work turns into noise – up to some 50+dB, which makes such devices impractical for medium-size music rooms [19], although some devices are claimed on their data sheets to be quieter. Filtering is effective down to 3µm, but a SARS-CoV-2 virion is some 20-30 times smaller than that [20], suggesting that an in-room recirculation device may not be effective prophylaxis against Covid-19.

Ventilation

So, on to ventilation. IMM seems fairly clear that effective air exchange is a solution to vva problems. Is it achievable in a music room retroactively? Household ventilation systems are widely available, and are widely installed in modern-build houses for a variety of reasons. Common models for entire houses shift nominally 350-600m^3 per hour, although I understand practical effectiveness is quite a bit less than that (some 60%?) inter alia because of air flow resistance in the tubing [19]. I understand they are generally aimed at a per-house rate of ½ House-Vol/hr [19]. There are also per-room installations, but they don't shift air at anything like the IMM-recommended rates. All these systems work to the same general principle: air is drawn from outside, prewarmed via a heat exchanger, filtered (at varying quality levels), circulated through the occupied space, filtered again, cooled in the heat exchanger, and exhausted to the outside. A key condition for such systems to work effectively is relatively good sealing of openings such as windows and doors, and there are standards and tests for such sealing capacity [21].

The ventilator itself is about 30dB loud, maybe louder at full power (my informal observation), but of course can be installed remotely. Such a system could be configured to ventilate just my music room. Just for this one room, I imagine airflow could be near-nominal: 450m^3 per hour yields 5.6+ Rvol/hr, and 350m^3 per hour yields 4.4- Rvol/hr.

However, as well as the structural installation of the circulation unit and pipes, room windows would almost certainly have to be replaced and the two doors modified to achieve the necessary sealing [21]. The devices themselves cost €3,000-4,000 plus tubing and installation; and then comes window replacement and door modification, so I would be looking likely at €8,000-€10,000. Whether to go with a higher performance device or a lower depends on whether I would consider the 6 Rvol/hr figure or the lower 4 Rvol/hr definitive, and we have seen that that is not decided. In any case, such an installation would be working to a different specification than the usual one (½ Rvol/hr), and there is no guarantee how that would work out.

The legal position

My final theme is law. Musical activity in public spaces (whether rooms or open air) is now part of law in my state of residence, North-Rhine-Westfalia in Germany, and most amateur choirs or music ensembles use public space in this sense to practice, and of course for performance.

Current law [22, §8(5)] regulates the use of public spaces (as above) for music and singing, and is being revised monthly. For 1st Oct 2020 to 31st Oct 2020, it simply requires adherence to the accompanying hygiene and infection-protection standards. Those standards [23, Section XII], also time-limited, are relatively detailed, encompassing how wind instruments should be cleaned during use, washing hands afterwards; how players should be situated (flutes in the front row of the orchestra), transparent material separating wind instruments from others, and so on. 2m radial distancing for everybody; 4m from musicians to audience; no audience of any sort in practice rooms. Apparently in the previous version (for September) it was required that each musician should occupy $7m^2$ of floor space, but in the current version that condition is no longer present [24, comment on differences].

I cannot say I am content with this guidance.

It is good on distancing, and on cleaning instruments. For example, dispose of your cloth after pulling through (There is no way I am going to throw my favourite chamois away, but I should obviously think how to clean differently if/when I play in ensembles outside my house). When you open the condensation-release valve on your trumpet, don't just shake out into the environment – catch what comes out, dispose of it appropriately, and disinfect. And then wash your hands. All good stuff.

But all to do with droplets and fomites. There is nothing on adequate ventilation/disinfection of the room, concerning aerosols. Which is what this article has mostly been about.

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Prof. Dr. Peter Bernard Ladkin

Peter Bernard Ladkin works in system safety and software-based system dependability. He is retired Professor at Bielefeld University, and Managing Director resp. CEO of British and German companies, both called Causalis, providing services in engineered-system RAMSS. His method Why-Because Analysis (WBA) is used worldwide by some 11,000 engineers. His flute playing is improving.

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