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Short communication

Pandemic management requires exposure science

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ABSTRACT

COVID-19 was first detected in Wuhan, China, on 8.12.2019, and WHO announced it a pandemic on 11.3.2020. No vaccines or medical cures against COVID-19 were available in the first corona year. Instead, different combinations of generic non-pharmaceutical interventions – to slow down the spread of infections via exposure restrictions to ‘flatten the curve’ so that it would not overburden the health care systems, or to suppress the virus to extinction – were applied with varying levels of strictness, duration and success in the Pacific and North Atlantic regions.

Due to an old misconception, almost all public health authorities dismissed the possibility that the virus would be transmitted via air. Opportunities to reduce the inhalation exposure – such as wearing effective FFP2/N95 respirators, improving ventilation and indoor air cleaning – were missed, and instead, hands were washed and surfaces disinfected.

The fact that aerosols were acknowledged as the main route of COVID-19 transmission in 2021 opened avenues for more efficient and socially less disruptive exposure and risk reduction policies that are discussed and evaluated here, demonstrating that indoor air and exposure sciences are crucial for successful management of pandemics. To effectively apply environmental and personal exposure mitigation measures, exposure science needs to target the human-to-human exposure pathways of the virus.

1. Introduction

No exposure, no risk, no harm applies to physical, chemical, and biological agents, including pathogens that cause contagious epidemic diseases. In the absence of effective vaccines or curative medication (pharmaceutical interventions) non-pharmaceutical interventions (NPI) to prevent or reduce the exposure of the susceptible people to the pathogens released by the infectious people, have been known for centuries. – to find and sequester the sick, to air with fire their goods and chambers, to shut any visitor of the infected house in the house wherein he inhabiteth for up to certain days (Defoe, 1722) – i.e., to test, disinfect, trace and quarantine.

Since the absence or limited effectiveness of the available means for pharmaceutical intervention is one of the key drivers in the leap from epidemic to pandemic, non-pharmaceutical interventions will remain critical for successful management of the current COVID-19 and any future pandemic. Hence, while acknowledging the importance of vaccination and medicines, the present article focuses on NPIs and policies that prevent or reduce human to human transmission or personal exposure to the SARS-CoV-2 virus.

Exposure science interconnects epidemiology, environmental, social, and behavioral sciences, identifies and analyzes exposure pathways and thus points out the potentials for exposure and risk prevention or reduction. Exposure science, therefore, possesses a huge potential for the assessment and control of the spread of a contagious disease. This was proposed in July 2020 by 239 international scientists (Morawska and Milton, 2020). Their views were mostly rejected for the first 15…20 months of the pandemic, and this has carried considerable public health consequences. This unfortunate situation highlights the need to elevate the public profile of exposure science, and to increase its education, research, and regulatory application in Europe and worldwide (Fantke et al., 2020; Bruinen de Bruin et al., 2022).

2. First responses to the pandemic

European Centre for Disease Prevention and Control divides the NPIs into three levels: Population level, reducing physical inter-personal interactions; Environmental level, including disinfection and ventilation; and Individual level, including respiratory and hand hygiene and personal protective equipment (PPE) (ECDC, 2021).

The efforts to curb the COVID-19 epidemic in Wuhan, China, began with the population level, i.e., cordon sanitaire that locked people into
their homes and demanded continuous location and health status reporting from every-one. The lockdown was prompt, invasive, and decisive. The policy successfully eradicated the virus from circulation in Wuhan and was lifted after 74 days (Pan et al., 2020) without a re-eruption of COVID-19. Other successful lockdowns in New Zealand, Finland and Victoria/Australia (in 2020) required 81…112 days to bring new infections down to 0…5 incidences/day.

When eradication of the virus isn’t complete, but population level restrictions, lockdowns, have cut the infections down to a controllable level, the logistic follow-up would be to restrict the contacts of the infectious/exposed individuals with all others by the test-trace-quarantine means. Most measures to control the pandemic in Europe in the spring of 2020, however, remained at population level (Bruinen de Bruin et al., 2020), became increasingly unpopular, were more or less lifted in the Autumn of 2020 and consequently the infections resumed to higher levels.

Japan chose already in March 2020 a policy to prevent SAES-CoV-2 transmission by indoor environmental quality control via the s.c. 3 Cs strategy targeting (i) closed spaces with poor ventilation, (ii) crowded spaces with many people, and (iii) close contacts (Azuma et al., 2020). Trusting the lessons learned from SARS (2002–2003) and the mobile communication technology tools developed for tracing and quarantine control, South Korea and Taiwan moved directly to test-trace-quarantine policy, thus avoiding national lockdowns. Except for Finland, the named countries applied stringent border controls but aimed at keeping domestic restrictions within their borders short and local and minimizing the interference with the lives of most people for most of the time.

Both the population and the personal level restrictions are limited to controlling the number and length of human contacts and/or the distance between the people. As such these measures are qualitative, rough, and socially disruptive.

Environmental and individual level policies to prevent and reduce the transmission of the virus in human contacts via hygiene, indoor air exchange and purification, hygiene, and PPE, are more precision targeted and less restrictive. They focus on defined exposures, that have specified sources, agents, exposure media and pathways from the sources to the recipients. In the case of COVID-19, the source is an infected human, the agent is the SARS-CoV-2 virus, and the media are air and contact surfaces. To effectively apply the environmental and individual measures more exposure data and knowledge need to be generated and applied to target the key steps on the human-to-human exposure pathways and thereby prevent more infections with less invasive actions.

3. Exposure pathways for SARS-CoV-2

In the first spring of the COVID-10 pandemic most public health authorities, starting with WHO, assumed that … transmission of the COVID-19 virus can occur by direct contact with infected people and indirect contact with surfaces in the immediate environment or with objects used on the infected person (WHO, 2020). The droplet-hands-face exposure pathway.

Since then, reports of COVID-19 outbreaks in crowded indoor spaces have amounted that could be poorly explained by droplet transmission, but easily by airborne transmission, or more precisely, the aerosol inhalation exposure pathway. While the latter was hotly debated, reminding some of the miasma theory (rejected in the 1880’s), it turned out that the widespread rejection of the aerosol transmission pathway was based on a misunderstanding that had found its way into textbooks and guidance documents 60 years ago and had stayed there since (Molteni, 2021; Wang et al., 2021). CDC (2021), ECDC (2020) and WHO acknowledged that the aerosol transmission is the dominant pathway.

• Current evidence suggests that the … virus can spread from an infected person… in small liquid particles when they cough, sneeze, speak, sing or breathe. Another person can then contract the virus when infectious particles that pass through the air are inhaled at short range (…short-range aerosol transmission)…

• The virus can also spread in poorly ventilated/crowded indoor settings, where people spend longer time. …because aerosols can remain suspended in the air or travel farther than conversational distance (…long-range aerosol transmission).

• People may also become infected when touching their eyes, nose, or mouth after touching surfaces or objects that have been contaminated by the virus.

Much of the credit for this clarification of the dominant exposure pathway for SARS-CoV-2 belongs to the tireless efforts of Prof Lidia Morawska (Morawska et al., 2021; Morawska and Milton, 2020), who was consequently honored by the TIME Magazine as one of the 100 most influential people of 2021.

There are two main pathways for the SARS-CoV-2 virus transmission visualized in Fig. 1. On the droplet-hands-face exposure pathway, the infected individual contaminates her hands and adjacent fomites by virus contaminated droplets and saliva –→ the recipient contaminates her hands by touching these fomites –→ and subsequently touching her face. On the aerosol-inhalation exposure pathway, the infected exhales [coughs, sneezes, shouts, etc.] releasing virus carrying aerosol into the air –→ the aerosol is carried by air currents –→ the vulnerable person inhales these aerosol droplets.

4. Preventing and reducing the exposure

Exposure can be prevented or reduced at every point on the pathway of the virus from the source to the recipient. The droplet-hands-face pathway and the aerosol-inhalation pathway, however, call for distinctly different exposure reduction strategies, and ignoring a major pathway may lead to invasive, expensive, and inefficient efforts.

The droplet-hands-face exposure pathway is restricted by screens to stop the large virus carrying droplets, by cleaning and disinfecting contact surfaces to eliminate live viruses, by wearing protective gloves, by washing and disinfecting hands to prevent or reduce virus transmission via the hands, and by avoiding touching one’s face. These measures, however, have no impact on aerosol-exposure.

Both exposure pathways are restricted by wearing face masks, observing physical distances and by minimizing the time spent in public indoor spaces and outdoor crowds.

The aerosol-inhalation exposure pathway is restricted by wearing face masks, preferably fitted FFP2/3 or N95 respirators to curb both the exhalation and the inhalation of virus containing aerosols, by air exchange to remove virus containing aerosols from the indoor space, and/or by air filtration to remove aerosol particles from the indoor air.

Face mask and respirator efficiencies – considering particle filtration and bypass – have been investigated in dozens of studies. One of the recent, measuring the filtration on real humans was published by Sickbert-Bennett et al. (2020).

Due to threshold and saturation the SARS-CoV-2 dose / COVID-19 response is likely to exhibit a typical S-shape, and therefore the real-world effectiveness of face mask or respirator wearing in preventing the infection is not necessarily directly proportional to the particle filtration effectiveness of the mask. Both the probability of the infection and the severity of its outcome are likely to depend on the viral dose in a non-linear fashion (Zhang and Wang, 2020; Van Damme et al., 2020). Infection prevention effectiveness has also been investigated in several studies. One of the most recent, conducted by Andrejko et al. (2021) in California demonstrated that compared to people who reported never wearing a mask, people who reported always wearing a surgical mask in public indoor settings were 66 % less likely and people wearing an N95 respirator were 83 % less likely to test positive for COVID-19 than people who did not.

Aerosol dispersion in indoor air, and the exposure reduction effects of control measures can be estimated by a wide choice of indoor air
ventilation, circulation and exposure models ranging from simple box models to advanced numerical fluid dynamics simulations (e.g., Vuorinen et al., 2020).

Several web-based indoor covid risk estimation tools have been published and made available for members of the general population (e.g., Dinklage et al., 2020; NIA, 2021) as well as for experts and professionals (e.g., Rutter et al., 2021, Jimenez and Peng, 2022) for the evaluation and comparison of the infection risks in different exposure settings and the impacts of various exposure reduction measures.

5. Reduction of the aerosol transmission in indoor contact settings

Transmission of the virus can be intervened at the source, along the pathway from the source to the recipient and at the point of intake of the virus by the recipient. Comparison of the efficiencies of the different means to reduce the exposure of the recipient, therefore, needs to bridge over the whole pathway.

For this purpose, the concept of intake fraction enables a strikingly simple exposure model. Intake fraction is defined as the fraction of an agent released into the environment that is eventually inhaled, ingested and/or dermally absorbed by the population (iF) (Bennet et al., 2002), or by the household occupants (iFh) in a residential indoor setting, or by an individual (iFi). For a particular setting iF integrates into a single dimensionless number everything that interferes the path of an agent from the source to the recipient(s). While iF values are simple to apply, they are often quite demanding to derive.

Fantke et al. (2017) characterized and estimated intake fractions for rural and urban outdoor and indoor sources of PM2.5 (fine particulate matter) using global databases. Ilacqua et al. (2007) used personal exposure, time activity and housing data from five cities in the EXPOLIS study (Hänninen et al., 2004) and Monte Carlo simulation to generate probability distributions of population and individual intake fractions for non-reactive airborne pollutants originating from residential indoor sources in five European cities. Despite their different approaches, the results [geometric mean (5th – 95th percentile)] of the two studies for iFi in residential settings broadly agree: Fantke et al. 0.013 (0.0005–0.062), Ilacqua et al. 0.006 (0.0009–0.041).

In the following example residential individual iFi values from Helsinki are taken from (Ilacqua et al., 2007), filtration efficiencies for face masks and respirators from (Sickbert-Bennett et al., 2020), and human respiratory particle emissions for different uses of voice from (Mürbe et al., 2021).

Eq. (1) draws from these data to estimate the inhalation exposure of individual A to the respirable particles exhaled by visitor(s) k in an urban residence. The exposure reduction measures that can be assessed with Eq. (1) are the presence of other people, their use of voice and wearing of face masks, ventilation and/or air filtration.

\[
\text{Exp}_A = p_A \cdot iF_i \cdot \sum_k (R_k p_k)
\]

where

\(\text{Exp}_A = \) inhalation of respiratory aerosol particles by individual A [#/sec].

\(p_A = \) proportion of aerosol particles that penetrate or bypass the mask of A in inhalation.

\(iF_i = \) individual intake fraction of inert air contaminants in residential indoor space.¹

\(R_k = \) emission rate of respiratory particles by visitor k [#/sec].²

\(p_k = \) proportion of aerosol particles that penetrate or bypass the mask of k in exhalation.

In the modelled exposure scenarios presented in Table 1, the exposed individual (A) and three visitors (k = 1…3) spend 1 h in a typical urban residence in Helsinki, Finland, and talk with each other. No exposure control measures are applied in the reference scenario that the exposure reduction scenarios are compared to. Seven scenarios involve just one measure, four are combinations of two and one of three measures to control the exposure.

Table 1 indicates the tremendous potential of indoor air hygiene and face masks/respirators for the reduction of exposure to respiratory aerosol particles. Increasing the air exchange from the 5th to the 95th percentile of the air exchange rate distribution within the residential

¹ In the current example the median, 5th and 95th percentile values of the respiratory iFi in Helsinki are used to represent typical, low and high indoor air exchange rate per occupant.

² While respiratory particles of a healthy individual are not infectious, the infectious aerosol particles exhaled by a sick individual are transmitted, removed, and diluted by the same phenomena.
building stock of Helsinki in 1996–97 or circulating the respective amount of indoor air through a particle filter with 90 % or better removal efficiency reduces the exposure by ca. 95 %. Wearing properly fitted FFP2/N95 respirators reduces exposure by 97 % and up to 99.9 % if every-one in the same indoor space uses them. Combining two or three measures multiplies the effect.

Relative to uncontrolled indoor exposure settings improving indoor air hygiene by ventilation or filtration, avoidance of loud voices, or personal wearing of masks and respirators may separately reduce the exposure to respiratory particles by 1/3 to 9/10, and in combination over 99.9 %.

5.1. Key messages based on the exposure considerations

“Any situation in which people are near one another for long periods of time increases the risk of transmission. Indoor locations, especially settings where there is poor ventilation, are riskier than outdoor locations. Activities where more particles are expelled from the mouth, such as singing or breathing heavily during exercise, also increase the risk of transmission” (WHO, 2021).

Each control measure that reduces the release of respiratory particles into the air or removes them from the air before they reach the airways of the recipient, makes a difference, but piling them on top of each other multiplies the benefit.

Transmission of the virus can be reduced 90 to 99 % by observing exposure control measures which do not prevent physical contacts between people. Concerts, cinemas, and theatres can be made safe the way it was done in the Vienna Philharmonic New Year Concert 1.1.2022. The audience was limited to 50 % of full capacity, and only vaccinated people with fresh PCR test results wearing FFP2 masks were allowed.

Of all practical, available, affordable and personal non-pharmaceutical interventions the exposure reduction potential of FFP2/N-95 respirators is highest, 97 % for a single user, 99.9 % when every-one in the same indoor space is using them. The respective real-life SARS-COV-2 infection risk reduction of self-reported “always wearing N95 respirator in public indoor settings” vs “never wearing a mask” was still 83 % (Andrejko et al., 2021).

Once more, application of exposure science is crucial for successfully managing the COVID19 and other pandemics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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| Applied exposure reducing measure (s) | Particle penetration of the mask used by host A | Indoor individual intake fraction | Respiratory particle emissions of visitors k = 1,2,3 (#/sec) | Particle penetration of the masks used by visitors k = 1,2,3 | Exposure of host A to respiratory particles (#/h) | Respiratory particle exposure reduction of host A |
|--------------------------------------|-----------------------------------------------|----------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|---------------------------------------------|----------------------------------------------|
| – 1 ventilation downgrade (5th percentile) | 100 % | 0.0163 | 200 | 100 | 300 | 100 | 100 | 100 | 35,208 | 366 % |
| 0 median ventilation (50th percentile) | 100 % | 0.0035 | 200 | 100 | 300 | 100 | 100 | 100 | 7,560 | 0 % |
| 1 ventilation upgrade (95th percentile) | 100 % | 0.0008 | 200 | 100 | 300 | 100 | 100 | 100 | 1,728 | –77 % |
| 2 silence | 100 % | 0.0035 | 13 | 10 | 20 | 100 | 100 | 100 | 542 | –93 % |
| 3 host wearing surgical mask | 67 % | 0.0035 | 200 | 100 | 300 | 100 | 100 | 100 | 5,065 | –33 % |
| 4 all wearing surgical masks | 67 % | 0.0035 | 200 | 100 | 300 | 67% | 67% | 67% | 3,394 | –55 % |
| 5 host wearing FFP2 / N95 | 3.5 % | 0.0035 | 200 | 100 | 300 | 100 | 100 | 100 | 265 | –97 % |
| 6 all wearing FFP2/ N95 | 3.5 % | 0.0035 | 200 | 100 | 300 | 3.5 | 3.5 | 3.5 | 9 | –99.9 % |
| 3 + ventilation upgrade | 67 % | 0.0008 | 200 | 100 | 300 | 100 | 100 | 100 | 1,158 | –85 % |
| 3 + silence | 67 % | 0.0035 | 13 | 10 | 20 | 100 | 100 | 100 | 363 | –95 % |
| 6 + ventilation upgrade | 3.5 % | 0.0008 | 200 | 100 | 300 | 3.5 | 3.5 | 3.5 | 21 | –99.97 % |
| 6 + silence | 3.5 % | 0.0035 | 13 | 10 | 20 | 3.5 | 3.5 | 3.5 | 0.7 | –99.99 % |
| 6 + silence + ventilation upgrade | 3.5 % | 0.0008 | 13 | 10 | 20 | 3.5 | 3.5 | 3.5 | 0.2 | –99.998 % |
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