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PERSPECTIVE

Back to Normal: An Old Physics Route to Reduce SARS-CoV-2 Transmission in Indoor Spaces

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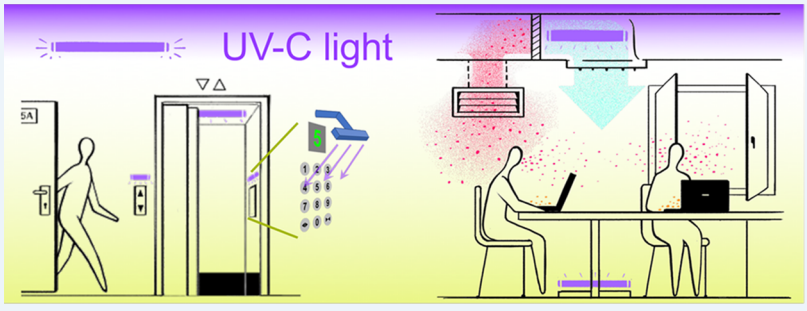

ABSTRACT: **We advocate the widespread use of UV-C light as a short-term, easily deployable, and affordable way to limit virus spread in the current SARS-CoV-2 pandemic. Radical social distancing with the associated shutdown of schools, restaurants, sport clubs, workplaces, and traveling has been shown to be effective in reducing virus spread, but its economic and social costs are unsustainable in the medium term. Simple measures like frequent handwashing, facial masks, and other physical barriers are being commonly adopted to prevent virus transmission. However, their efficacy may be limited, particularly in shared indoor spaces, where, in addition to airborne transmission, elements with small surface areas such as elevator buttons, door handles, and handrails are frequently used and can also mediate transmission. We argue that additional measures are necessary to reduce virus transmission when people resume attending schools and jobs that require proximity or some degree of physical contact. Among the available alternatives, UV-C light satisfies the requirements of rapid, widespread, and economically viable deployment. Its implementation is only limited by current production capacities, an increase of which requires swift intervention by industry and authorities.**

Pandemics created by novel viruses from animal reservoirs have become recurrent events in our globalized world. The recent outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a reminder that, once a virus emerges in the human population for the first time, it can rapidly spread worldwide and put our wellbeing in danger if it is not contained from the very beginning. Viral spread is particularly probable if the virus can be transmitted through the air, has a short incubation time, and is highly infectious. Our strongly interconnected society has a large fraction of the population concentrated in megacities hosting millions of inhabitants with frequent human interactions. In addition, our society has access to efficient travel systems that enable reaching even remote places within hours, thus fostering dissemination of diseases.[1] Consequently, managing pandemics is indeed a huge challenge for any government or social organization.

The recent SARS-CoV-2 pandemic has shown that initial measures of temporary confinement of citizens can be effective in curbing the spread of the virus and preventing the collapse of health systems.[2] However, confinement causes a huge burden on national and global economies, negatively impacting businesses and individuals' physical and mental health. In addition,

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developing countries cannot assume such burdens and are instead forced to endure the pandemic. Consequently, in both developing and developed economies, there is strong motivation to end confinement and, instead, to implement measures that enable some degree of physical proximity between individuals, allowing them to have long interactions in indoor spaces. To contain the spread of SARS-CoV-2 and to limit similar outbreaks in the future, prevention measures that can be rapidly adopted are an excellent investment in shared environments. Moreover, such prevention measures should be planned as part of future infrastructure in workplaces, public buildings, and mass transit systems.

Air-transmittable viruses such as influenza viruses,[3] the common-cold rhinoviruses, or the new SARS-CoV-2 virus are emitted from an infected individual during coughing, sneezing, talking, or even breathing.[3−10] These physiological actions produce aerosols made of droplets of various sizes that may carry infectious viruses and initiate new infection events when inhaled by others. Importantly, the specific size of the droplets determines their airborne lifetimes and, thus, the duration over which passing individuals may be exposed to the virus. Droplets larger than ∼100−200 μm settle down rapidly under the action of gravity and rarely reach distances beyond a few meters from the release point,[8,11,12] whereas droplets smaller than 10 μm (5 μm) with settling speeds below 3 mm/s (0.8 mm/s) can stay airborne for ∼10 min (>30 min in still air) or longer if they shrink by water evaporation and/or get dispersed by air currents.[11,13] Droplets emitted in the intermediate size range (∼10−100 μm) can also shrink due to evaporation and be equally dispersed.[13] Factors such as airflow speed, temperature, and humidity can also affect the transmission rate associated with infectious aerosols.[14,15]

Recent studies indicate that weather conditions do not strongly affect SARS-CoV-2 spreading.[16,17] Nevertheless, temperature and humidity influence virus survival on surfaces,[18] which, together with the type of supporting material, affect the measured persistence times of viral genetic material, ranging from hours to days.[19,20] Humidity plays an important role in viral transmission and is an especially important factor in relation to social and working environments because cold humid air from outdoors suffers a significant drop in humidity when entering indoor spaces.[21] Consistent with this finding, animal models show that respiratory droplet transmission of influenza in ferrets is more efficient in a 30% relative humidity environment and least efficient above 50%.[22] Relative humidity has been hypothesized to play a role in the determination that aerosols are the most efficient chain of transmission in temperate regions, although this parameter may also be responsible for a different transmission preference in humid and warm regions, where heavier, water-laden, airborne virus-containing droplets tend to settle on surfaces, thus favoring contact transmission.[23]

The ability of SARS-COV-2 to be transmitted a few days before infected individuals feel any symptoms[24] and also by undiagnosed asymptomatic individuals[25] further complicates prevention and demands intervention in all frequented indoor spaces. Reducing exposure to air-transmittable viruses requires inactivation of both (i) airborne viruses in aerosols and (ii) viruses deposited on actively used surfaces.

A simple rate-equation model that accounts for susceptible (S), infected (I), and resistant (R) individuals, formulated nearly a century ago,[26,27] quantifies epidemics by the so-called reproduction number R. The latter reflects how many new infections are produced on average by every infected person. An epidemic grows or decays roughly exponentially if $R > 1$ or $R < 1$, respectively. The initial phase of the current SARS-CoV-2 pandemic was characterized by a high R value of ∼2.5 when no mitigation measures were implemented, and all individuals were susceptible to the virus. With an increasing number of resistant individuals that have successfully defeated the virus by their immune responses, the epidemic will naturally slow down and terminate once so-called herd immunity is reached. This state would require at least a fraction $1 - 1/R \sim 60\%$ of the population to be immune to the virus, although a straightforward solution of the SIR model[28] actually predicts higher values depending on the dynamical evolution of the pandemic, with 20% of people simultaneously infected at the peak of contagions. More sophisticated models taking into account social habits as well as geographical distribution and interconnections of the population also predict similarly large numbers of infections.[29−31] Further elaboration of the simple SIR model explains the benefits of containment measures[2,32] and forecasts subsequent waves if those measures are relaxed.[30,31,33,34] These models and forecasts, therefore, emphasize the need for economically sustainable mitigation actions to either bring R below 1 (suppression strategy) or at least reduce its value so that a high peak of infections can be averted (mitigation strategy).

The recommended measures of social distancing,[2] frequent handwashing,[35] adoption of physical barriers such as surgical masks and other personal protection equipment,[3,35−39] travel restrictions,[40] and frequent direct disinfection of surfaces are effective in reducing the risk of contagion, so they are recurrently recommended in influential surveys.[41,42] However, within indoor spaces, such as shared offices, classrooms, healthcare facilities, and public transport vehicles, these methods may not reduce viral transmission rates to a sufficiently low level to prevent exponential growth of the pandemic. Specifically, with its relatively high R number of ∼2.5, the SARS-CoV-2 pandemic requires the adoption of additional measures to supplement those mentioned above. The need for such additional measures is particularly acute in hospitals, where the high densities of infected individuals have already led to high rates of infection among healthcare professionals in epidemic hotspots, and consequently, new protocols are being tested.[43]

In this Perspective, we discuss additional measures to reduce SARS-CoV-2 transmissions in indoor spaces such as office spaces. Due to the urgency to act on a global scale, we advocate for one measure that is particularly efficient, easily deployable, and economically affordable: virus inactivation by ultraviolet (UV) light. Nevertheless, the production of a sufficient number of source elements might be a limiting factor that requires fast intervention by industry and government authorities in order to address the foreseeable demand.

Due to the urgency to act on a global scale, we advocate for one measure that is particularly efficient, easily deployable, and economically affordable: virus inactivation by ultraviolet light.

Pathways of Infection in Daily Life. Figure 1a illustrates different pathways of virus transmission classified into two distinct categories: (1) air transmission of viruses in droplets exhaled by infected individuals and inhaled by healthy

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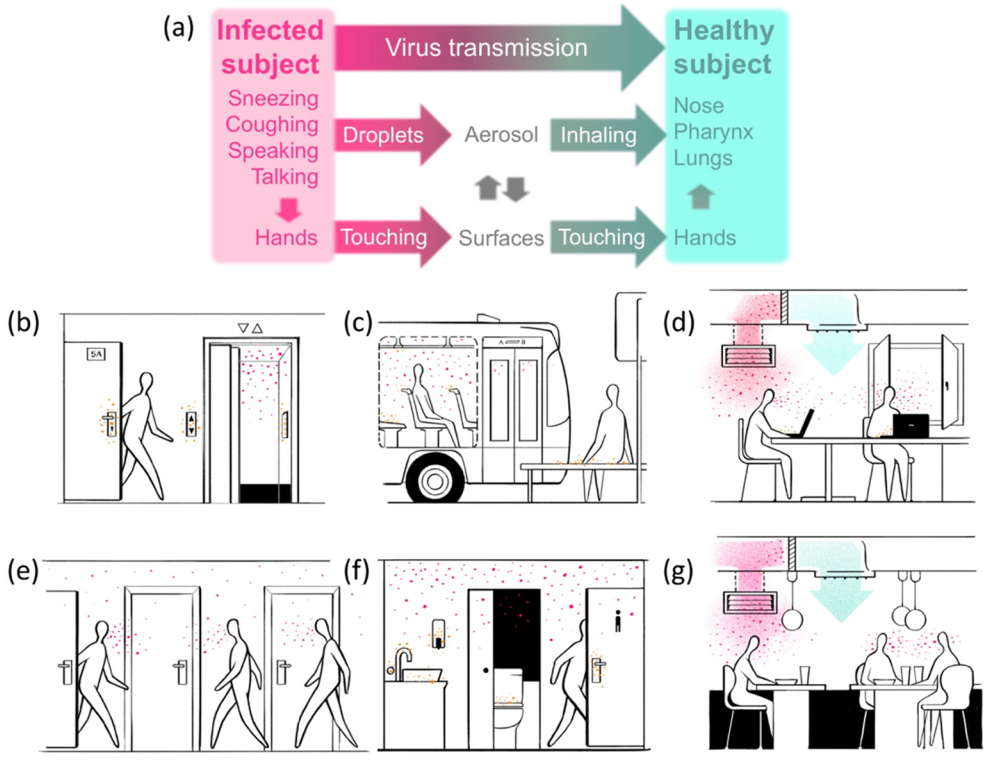

Figure 1. Pathways of viral infection in everyday life. (a) Simplified scheme of aerosol and contact pathways for virus transmission. (b–g) Pictorial description of exposure to virus in everyday activities when (b) using elevators; (c) taking public transportation; (d) spending time in shared indoor spaces such as workplaces, schools, and centers for other social activities; (e) walking through corridors; (f) using common facilities such as toilets, office pantries, and storerooms; and (g) dining at restaurants or accessing other public services with high customer turnover. Colored items indicate airborne viruses (red dots), surface-deposited viruses (orange dots), contaminated-air flow (reddish arrows), and fresh/cleaned-air flow (blueish arrows).

individuals; and (2) surface transmission of viruses deposited on surfaces from either exhalations or hand contact. Infected individuals may spread viruses through coughing and sneezing but also through breathing and speaking in the presence of healthy, susceptible individuals. A long series of studies has revealed a relation between ventilation in buildings and the rate of infection of air-transmittable diseases,[44] therefore prompting recommendations on the use of ventilation systems to minimize the risk of infection.[45,46] In addition, recent research has conclusively shown rapid spreading of airborne pathogens in indoor spaces within a few minutes using methods that include fluid-dynamics simulations[47,48] and experimental measurements of aerosol emission during speech,[4,5,7,10] coughing,[4,8] and sneezing.[8] Analyses in hospitals have recently provided *in situ* evidence supporting this conclusion.[9] Incidentally, the level of loudness while talking determines the size of the emitted droplets,[4,7] which in turn plays a decisive role on the rate of transmission.[49] Coughing, sneezing, and talking in confined air volumes therefore pose a real risk when several individuals, some of whom may potentially be infected, have to share the same room for hours. Obviously, the density of people inside buildings is a critical factor that determines the rate of transmission.[50] Contact with surfaces that are frequently used by many people and on which the virus can survive for hours,[19] such as door bells, door handles, and handrails, may also represent another efficient source of transmission.

In Figure 1b–g, we sketch common scenarios in which airborne and surface-mediated virus transmission can take place during daily life activities. When leaving an apartment building or entering indoor workplaces, elevator buttons and door handles (Figure 1b) offer surfaces of reduced area that are likely touched by many individuals and, thus, facilitate virus transmission. In addition, airborne viruses exhaled from infected individuals can be dispersed and effectively transmitted to healthy people in confined spaces such as elevators (Figure 1b), office pantries, and shared toilets (Figure 1f). The latter can additionally be contaminated by transfers of microorganisms to the air during flushing.[51,52] Buses and other means of public transportation[53] (Figure 1c) also involve many individuals sharing confined air in small spaces as well as frequent hand contact with small area surfaces such as handrails. Although often involving larger volumes, the work environment in shared offices (Figure 1d) and workshops can foster virus transmission as well because people spend long working hours inside of them. Similarly, public indoor spaces such as shops, restaurants, and cafeterias (Figure 1g) involve a high turnover of customers and, thus, represent another likely scenario for efficient virus transmission.

Social distancing measures, such as limiting the density of people in confined spaces like those sketched in Figure 1, can help reduce virus transmission, but these measures come at a high cost in the long run because they give rise to a considerable reduction in economic activity. Additional measures for preventing viral spread are required in order to enable a sustainable level of activity while reducing the negative economic impact of the ongoing pandemic.

Preventing Viral Spread. Simple physical barriers (handwashing, facial masks, *etc.*) are being strongly encouraged because they are efficient, easily deployable, and inexpensive means to reduce viral spread.[2,35,36,38−42] Still, each of these

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measures presents specific problems, and it is questionable as to whether they are sufficient to reduce the reproduction number R below 1 without maintaining social distancing because their efficacy depends on the fraction of the population that fully comply with them. With the graphics in Figure 1b–g, we illustrate everyday scenarios in which these measures may have limited efficiency, particularly in preventing the spread of airborne viruses in frequently used confined spaces (*e.g.*, toilets, elevators) and surface-deposited viruses in small-area surfaces such as handles, buttons, and handrails.

Additional measures for preventing viral spread are required in order to enable a sustainable level of activity while reducing the negative economic impact of the ongoing pandemic.

Additional measures to reduce virus propagation can be adopted at three different levels: (1) by redesigning the future infrastructure of shared spaces such as offices, toilet rooms, buses, and trains; (2) by emphasizing further compliance from people with the aforementioned measures; and (3) by deploying measures that will inactivate viruses that are emitted in indoor environments and become airborne or that are deposited on surfaces. Level (1) requires long-term planning and might be an excellent option for future pandemics, but it does not address the acute needs of the current SARS-CoV-2 situation. Level (2) depends strongly on political and social considerations that may vary across countries and, therefore, does not provide a complete solution on the global scale. We focus here on level (3) measures such as washing and wiping surfaces, spraying disinfectants, or illumination with UV-C (200–280 nm wavelength) light sources. The efficiency of each depends on how much they fulfill the following requirements:

- Fast implementation. The financial burden of sustaining the level of social distancing required to prevent exponential growth of the pandemic is immense. Particularly after the first wave, the possibility of recurring waves of infection and potential changes in virus pathogenicity triggered by mutations is of major concern. Timeliness is paramount to address these concerns.
- Scalability. The implementation of new measures involves massive economical, geographical, and social scales, affecting billions of workers in possibly hundreds of millions of shared workspaces and, therefore, requires similarly high numbers of physical units to be handled and produced at unprecedented rates.
- Affordability. The investment needed to act on a sufficient fraction of workspaces worldwide may quickly reach multibillion dollar figures, a demand that many countries are not prepared to spend, unless these measures can be made sufficiently inexpensive.

Preventing airborne virus transmission requires frequent air renewal and/or exposure to conditions that are lethal for the virus but innocuous to humans. Disinfection methods as simple as continuous renewal of air through opening windows can be efficient,[54] but this is not a reasonable option in many climates. Air conditioning (AC) and central heating systems provide continuous access to circulating air (100% room volume circulation every 10–20 min[45,46] with fresh air replacement every 40–60 min and higher rates in sensitive environments such as research laboratories and operating rooms), incorporating sophisticated methods to control air flow and ventilation in multizone spaces.[55]

Contaminated particles can be filtered out from air circulating in ventilation systems,[56,57] and viruses can be directly inactivated using chemicals[58−61] or by exposing them to UV-C light.[62] In particular, air filters have proven to be efficient in substantially reducing the concentration of >1-μm-sized particles from air, whereas existing electrostatic precipitators eliminate even smaller particles down to <0.1 μm with ∼90% efficiency;[56] however, these methods involve costly and time-consuming installations, which are suitable for large volumes but require long-term planning. Similar considerations apply to virus inactivation through plasma devices.[63] In addition, ozone,[58] hydrogen peroxide,[59,60] and other chemicals[61] have been proven to be efficient means of virus disinfection in indoor spaces, but these substances are harmful to humans, so they can only be used while people are outside, subject to strict limits of concentration (*e.g.*, >200 ppb ozone is required to inactivate RNA viruses, but >75 ppb exposure for hours becomes harmful, particularly for individuals with asthma[58]).

With filters and chemicals requiring long-term planning and/or the evacuation of people while in use, certain wavelengths of UV-C light emerge as the most promising solution to act swiftly on the SARS-CoV-2 pandemic because UV-C light meets the aforementioned requirements of fast, scalable, and affordable implementation. Direct comparison between UV-C light and hydrogen peroxide cleaning reveals similarly high efficiencies, yet with certain pros and cons: although UV-C light acts faster, access to shadowed areas can be a problem,[60] which could be mitigated through intensive use of ventilation systems.

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UV-C Protection and Its Implementation. UV-C light has been applied in sterilization for over a century, including in the treatment of the disease lupus vulgaris, for which Niels Ryberg Finsen received the Nobel Prize in Medicine in 1903. This spectral range of light lies right at the edge of the UV water transparency window, where water is transparent enough to prevent light attenuation inside micron-sized exhaled droplets, so that the illumination can inactivate viruses contained in them. Early studies had already shown the benefits of using UV-C irradiation to prevent the spread of measles in rural schools.[64] Currently, UV-C light is commonly used in water disinfection,[65] and its use has been proven to reduce air transmission of tuberculosis[66] and airborne viruses.[62,67,68] Specifically, fluorescence lamps are widely used sources to produce light at a wavelength of 254 nm, which inactivates pathogens through efficient absorption by their DNA or RNA (Figure 2g). The inactivation efficiency grows exponentially with the dose, which is proportional to both the exposure time and the light

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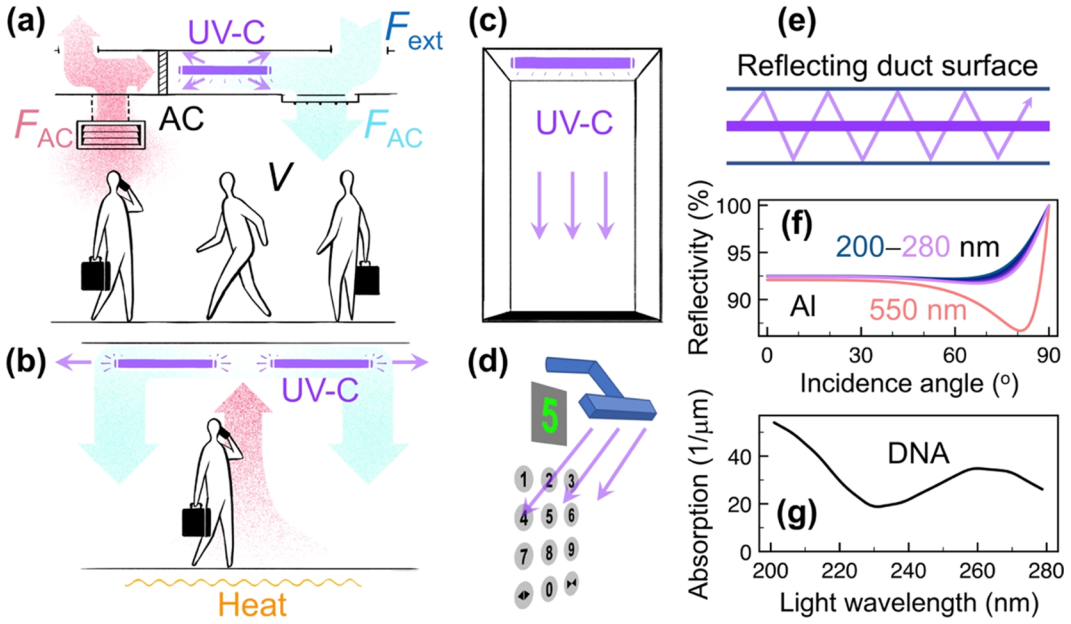

Figure 2. Reduction of viral spread through UV-C light. (a) UV-C sources placed inside air-conditioning (AC) ducts. (b) UV-C collimated *wallpaper ceiling* illumination combined with temperature-driven air circulation. (c) Direct UV-C exposure of toilets, elevators, doorways, and other small-volume spaces while not in use. (d) Local UV-C light applied to frequently used contact elements (buttons, handles, and handrails). (e) Reflecting surfaces placed near UV-C sources in ducts can create multiple light passages through the same volume of air, thus optimizing the efficiency. (f) Reflectivity of aluminum in the 200−280 nm UV-C range obtained from optical data;[80] the reflectivity at a visible wavelength of 550 nm is shown for comparison. (g) Optical absorption of DNA obtained from optical data in the UV-C range;[81] RNA has a similar spectral profile of absorption.

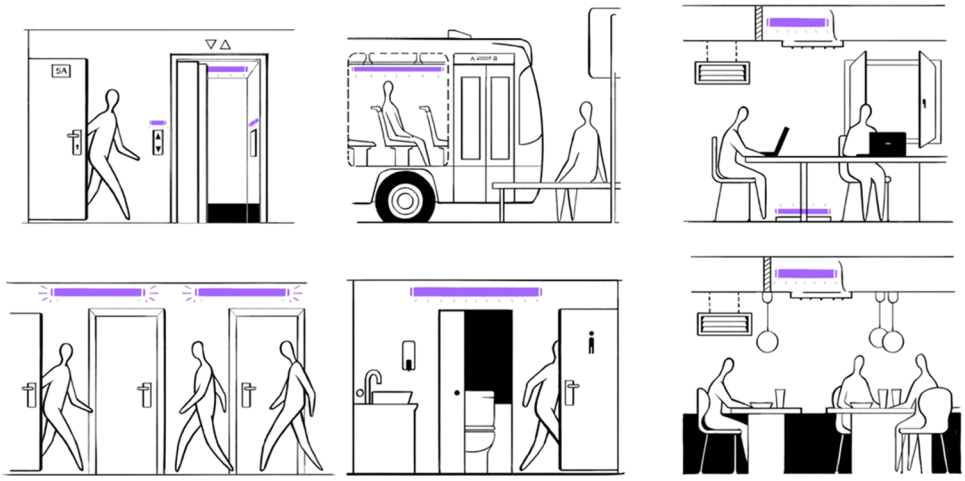

Figure 3. UV-C light in everyday life scenarios. We reproduce Figure 1b−g with placements of UV-C light sources to reduce virus propagation.

intensity.[62] The fraction of inactivated viruses is roughly given by $1-10^{-F/F_0}$, where F is the applied fluence (in units of energy per area), whereas F_0, which stands for the fluence needed to inactivate 90% of viruses, is dependent on the light wavelength and the type of pathogen. In particular, values in the $F_0 = 3-12$ J/m^2 range were found using 254 nm light to inactivate airborne viruses with efficiencies depending on whether they contained RNA or DNA with single or double strands.[69] For H1N1 influenza, a value below $F_0 = 15$ J/m^2 was obtained at a wavelength of 222 nm.[70] In a more relevant study to SARS-CoV-2, Walker and Ko found $F_0 = 6.6$ J/m^2 in murine hepatitis virus (MHV), a coronavirus, using 254 nm light.[71] More recently, a different study reported close to 100% inactivation of MHV-A59 and MERS-CoV coronaviruses after 5−10 min exposure[72] but, unfortunately, without referring details on the fluence used. Importantly for the present survey, the germicide action of UV-C light placed inside AC ducts has already been demonstrated.[73] These results support the use of UV-C disinfection to mitigate the SARS-CoV-2 pandemic,[41] for which the treatise by Kowalski[62] provides an excellent summary of the state-of-the-art in this technology.

UV-C light can produce eye damage when exceeding the recommended and experimentally validated limit of ∼60 J/m^2 fluence exposure over several hours.[74] In addition, despite its relatively short skin penetration depth (∼2 μm at 250 nm wavelength[75]), UV-C radiation produces carcinogenic effects because it is absorbed by human DNA (Figure 2g), as well as by the cytoplasm of cells.[76] Paradoxically, this problem is less severe for more energetic light at shorter wavelengths, and recent studies have concluded that 207[77] and 222 nm[78,79] wavelengths

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are less damaging for humans than 254 nm but have similar efficiency to inactivate pathogens. Unfortunately, the lower the wavelength of UV-C light, the more effective it is at generating harmful ozone. Recent studies promote the prospects of far UV-C light (wavelengths of ∼200−230 nm) as a regime of low risk to human health, yet still with low ozone production.[77−79]

Providing the conditions to resume work with a higher degree of safety in the current SARS-CoV-2 pandemic requires implementing protection measures while people are oftentimes present in the workplace. For this purpose, UV-C light sources could be distributed with no direct optical path to humans in the ducts of ventilation systems (Figure 2a).[62] As an alternative, one could instead use horizontally collimated illumination of a fraction of the room height near either the ceiling or the floor, adding air circulation through temperature-controlled elements such as heaters placed near or beneath the floor (Figure 2b). Commercial solutions for these possibilities already exist.[62] Stand-alone systems consisting of UV-C elements hidden inside a pipe combined with fans to produce intense airflow through them could be an additional option, although the associated turbulent air dynamics could have unknown consequences on the dispersion of exhaled droplets. These solutions could be adequate to increase protection against virus transmission in office spaces, classrooms, and restaurants (Figures 1d,g and 3).

Smaller spaces such as toilets, elevators, and office pantries (Figures 1b,f and 3) are used only intermittently and involve a high turnover of people. These spaces could be protected by safely exposing them to a high intensity of UV-C radiation while not in use (Figures 2c), which could guarantee a virus-free space when a new user enters. In addition, their usable time could be automatically allocated in order to reserve a dwell time during which UV-C irradiation is applied. This approach could be equally practical in public transportation, with periodic irradiation cycles after a certain number of stops or time of continuous use. A similar concept could be applied to motion-inactivated UV-C illumination that would serve as a protective barrier in passageways and corridors (Figures 1e and 3). We also note that frequently touched surfaces, such as buttons (Figures 2d and 3), handles, and specific segments of handrails, could be directly and continuously exposed to weak UV-C sources aimed at them, as they involve minor risk from eye irradiation or a limited exposure time on hands. Hand-held UV-C devices could be used as well for quick disinfection of these elements and of surfaces in public transportation vehicles (Figures 1c and 3) as an alternative to cleaning through more time-consuming conventional methods.

We can estimate the UV-C power needed to clean air through typical ventilation systems by considering a few of their relevant characteristics extracted from American[45] and European[46] standards. These systems generally inject a volume of virus-free exterior air inside the building equivalent to 1−1.5 times the building volume per hour (*i.e.*, $F_{ext}/V = 1-1.5/h$; see Figure 2a); such fresh air is mixed with 1−2 times its share of recycled air (*i.e.*, totalling $F_{AC}/F_{ext} = 2-3$); disinfecting the latter can thus bring the rate of clean-air replacement to ∼2−4.5 times per hour at the cost of cleaning a volume of air per hour equal to 1−3 times the building volume. At full occupation, the building volume per person is ∼30 m^3, thus requiring $V_p \sim 30-90$ m^3 of recycled air disinfection per hour per person. Taking standard air circulation speeds $v \sim 1-2$ m/s in ventilation systems and a representative duct with a length $L_d = 1$ m, and cross-sectional area $A_d = 1$ m^2 with an optical path to a single UV-C light source, we can achieve 90% virus inactivation in the recycled air with an output UV-C power of $\sim vA_dF_0/L_d$, which yields 10−20 W when plugging the 1/10 attenuation fluence $F_0 \sim 10$ J/m^2 discussed above. This power alone can disinfect a volume per unit time $\sim vA_d$, and, therefore, combining these expressions, the required UV-C output power per person is $\sim F_0\ V_p/(L_d \times 3600$ sec) ∼80−250 mW. In this rough estimate, we assume illumination collimated along the duct, but the actual light power demand is, of course, dependent on the geometry of the ventilation system. In fact, the illumination efficiency can be increased by creating multiple reflections in ducts coated with aluminum or simply covered with aluminum foil (Figure 2e,f),[62] as this material offers a reflectivity $r > 90\%$ that can thus reduce the UV-C power demand by a factor $1/(1 - r) > 10$ (upper bound estimate) because all of the reflected light is available for virus inactivation. For future designs, more sophisticated dielectric-based duct coatings could push r closer to 100% and thus reduce the light power demand even further, while also minimizing the potential damage of stray light reaching people's eyes and skin. In brief, ventilation systems operating at their maximum fresh-air injection capabilities can renew air at a rate of 1−1.5 times per hour, but this rate can be increased 2−3-fold with a modest investment of <0.25 W output UV-C power per person or even lower power of a few mW per person after optimizing multiple reflections in the ventilation ducts.

Upper- or lower-room UV-C illumination (Figure 2b) can also be an efficient means of virus inactivation, but this approach requires more careful analysis of potentially hazardous stray light, thus making it less amenable to short-term implementation. The efficiency then depends on the fraction of illuminated to total air volume, the use of multiple reflections, and the existence of vertical air circulation. However, we expect similar efficiencies as in the ventilation systems discussed above.

Disinfection of small confined spaces such as toilets and elevators (Figure 2c) could be achieved by shining UV-C light while they are not in use, requiring an illumination power inversely proportional to the dwell time between uses. Because of their small share of total volume in buildings, their share of power demand should still represent a relatively minor investment. In turn, disinfecting such spaces could have huge health protection impact in view of their high frequency of use.

We further identify surfaces of small objects such as elevator buttons (Figure 2d), which are touched at intervals of >10 s by many individuals, as a suitable target for UV-C protection. They would require a UV-C intensity <1 W/m^2 to accumulate a fluence $F_0 \sim 10$ J/m^2 between uses necessary to achieve 90% disinfection (see above). Thus, a typical element with a surface area of ∼0.01 m^2 could be continuously disinfected using just a marginal <10 mW UV-C power, aimed at it, for example, from a small light-emitting diode (LED).

A pertinent question is whether industry can satisfy the demand for UV-C sources for massive protection at a global scale. Currently, low-density fluorescence lamps are commonly used to generate UV-C light with 30−40% power efficiencies at 254 nm wavelength. However, LEDs have emerged as an alternative capable of emitting light down to wavelengths as low as 210 nm.[82] The efficiencies of LEDs in the UV-C range are comparatively poor (∼1−2%) though,[83] still small compared with fluorescence tubes. Nevertheless, their faster and more versatile operation has pushed LED sources to take >40% of the UV market.[84] To cover large volumes, high-power sources are needed, such as microcavity plasmas, which have been shown to be capable of delivering >20% efficiency at a 172 nm emission wavelength.[85] Importantly, low-density fluorescence lamps are

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by far cheaper per output watt (~$5/W rough estimate based upon inspection of current Amazon.com listings) than LEDs or high-density fluorescence lamps (~$100/W), although the harmful effects that UV fluorescence lamps have on human health demand avoiding direct exposure of eyes and skin, as discussed above. Putting together the above figures, disinfection with fluorescence lamps could be implemented at a cost of a few dollars per person with minimum changes in infrastructure. Thus, a global capital investment of a few billion dollars could protect on the order of $\sim 10^9$ indoor workers worldwide. However, the global market for UV-C light barely reaches one billion dollars per year currently, so it may have difficulty coping with the expected rise in demand originated by the SARS-CoV-2 pandemic.

The need for compact and efficient UV-C light sources clearly demands the investigation of alternative approaches besides traditional low-density discharge tubes, high-density plasmas, and the more recent LED devices. An alternative may be offered by relying on energetic free electrons as a source of excitation. Specifically, crystalline samples of hexagonal boron nitride (hBN) were shown to produce intense cathodoluminescence (CL) emission at a wavelength ~215 nm upon bombardment by 20 keV electrons,[86] which could even result in lasing when using an optical cavity. Initially thought to be associated with a direct band gap of this material, a subsequent study confirmed that the emission was related to the presence of an indirect band gap[87] in which phonons provide the required momentum compensation during radiative de-excitation. This method was verified using field emission sources with electron energies down to 8 keV, which resulted in UV-C light generation at a wavelength of 225 nm from hBN powder,[88] although the efficiency was <1%. Other materials with suitable band gaps may offer more efficient paths to UV-C light generation through similar incoherent CL processes.

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Although all of the aforementioned methods rely heavily on the electronic characteristics of a selection of high-purity materials (*e.g.*, Hg and Xe in tubes, AlGaN in LEDs, and hBN in CL), the Smith–Purcell effect[89] provides another approach to generate UV-C radiation that is less sensitive to the nature of the material employed and can lead to highly directed and coherent emission. Light is then emitted due to the passage of a free electron near a periodic grating, whereby the electromagnetic interaction between the electron and each groove results in a coherent source that produces light with a well-defined relation between wavelength and emission direction. This effect, whose analogues have been extensively exploited to generate X-ray radiation in synchrotrons and free-electron lasers employing relativistic electron beams, has long been speculated to serve as a mechanism for the efficient generation of UV radiation using gratings with periods of tens of nanometers.[90] Recently, Smith–Purcell emission down to 230 nm wavelength has been demonstrated,[91] and a strong reduction in the grating period has been shown to provide a promising way of generating UV-C radiation with few kiloelectronvolt electrons.[92]

Further investigation into these alternative mechanisms of UV-C light generation demands an effort from the research community, which can certainly benefit from the latest advances in nanofabrication and compact electron sources.

CONCLUDING REMARKS

The SARS-CoV-2 outbreak is posing an extraordinary challenge that requires swift worldwide action for the massive deployment of affordable and ready-to-apply measures to abate transmission in indoor spaces, such as work settings. Physical means of reducing transmission should require relatively low costs and virtually no alteration of working conditions. In addition to massive monitoring and follow up of contacts of new infections, widely advertised measures such as wearing masks[25] and frequent handwashing are proving useful but can still fall short of preventing the spreading of the SARS-CoV-2 virus. Additional preventive measures also need to adapt to different regions and environments, where transmission routes for SARS-CoV-2 vary. Our succinct analysis of such possible measures leads us to argue that UV-C light stands out as a promising candidate that satisfies the above criteria and, in particular, that can be deployed in the short run with an affordable capital investment. The efficiency of this measure should be extensively monitored by studying correlations with the outcome of widespread testing.

> The SARS-CoV-2 outbreak is posing an extraordinary challenge that requires swift worldwide action for the massive deployment of affordable and ready-to-apply measures to abate transmission in indoor spaces, such as work settings.

Although we focus on work/public spaces such as offices and shopping areas, the effectiveness of UV-C light may require additional considerations in schools and other environments where social distancing is more difficult to maintain. In particular, prevaccination-era studies showed that UV light could reduce spreading of viruses such as measles, chickenpox, and mumps among school children[64] but with an effectiveness that was very dependent on the afterschool environment (*e.g.*, crowded accommodations and public transport).[93] UV-C light can also be kept in place for the long-term, as it should help reduce infections by pathogens, but should not preclude children from entering into contact with those microorganisms that are thought to be important in the development of the immune system (the so-called hygiene hypothesis[94]).

Coping with the SARS-CoV-2 pandemic demands that we use every affordable measure and should probably involve mixed solutions adapted to each environment. The fast evolution of this crisis also requires that these measures be continuously monitored for effectiveness. Nevertheless, even when the SARS-CoV-2 pandemic has passed, it will be important to maintain the generated knowledge and resources to deal with similar pandemics in the future. The global, high interconnectivity of human societies makes them inevitable.

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Notes

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