Contact transmission of SARS-CoV-2 on fomite surfaces: surface survival and risk reduction

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There is an unprecedented concern regarding the viral strain SARS-CoV-2 and especially its respiratory disease more commonly known as COVID-19. SARS-CoV-2 virus has the ability to survive on different surfaces for extended periods, ranging from days up to months. The new infectious properties of SARS-CoV-2 vary depending on the properties of fomite surfaces. In this review, we summarize the risk factors involved in the indirect transmission pathways of SARS-CoV-2 strains on fomite surfaces. The main mode of indirect transmission is the contamination of porous and non-porous inanimate surfaces such as textile surfaces that include clothes and most importantly personal protective equipment like personal protective equipment kits, masks, etc. In the second part of the review, we highlight materials and processes that can actively reduce the SARS-CoV-2 surface contamination pattern and the associated transmission routes. The review also focuses on some general methodologies for designing advanced and effective antiviral surfaces by physical and chemical modifications, viral inhibitors, etc.

1. Introduction

Fomites can be contaminated by two means: contamination directly by respiratory droplets and by cross-contamination. The dynamics in the transfer of SARS-CoV-2 is very complex as it involves multiple variables including transfer between the hand and environment. It may also be said that airborne particulates act as the main carriers of SARS-CoV-2. The total quantity of virus exposed from a person depends on what way the viruses were transferred from the infected person and also on the amount or segment of viruses that were transferred to the surfaces, mucous membranes and hands. The factors affecting the transfer of viruses consist of skin surface characteristics, type of surface, temperature and humidity [1]. The studies which have been reported on the inactivation of influenza A on the skin surface were due to the antiviral properties that causes the quick inactivation on the hands of the person [2,3]. However, there are no studies reported on how the human skin is inactivating SARS-CoV-2. The other factors responsible for the transmission of SARS-CoV-2 on fomite surfaces are through the personal behaviours involved in sneezing, coughing into their sleeves or hands or to/through the person wearing personal protective equipment. In general, the transfer of virus from porous surfaces to hands is lower than the non-porous surfaces. Mathematical modelling and experimental studies will be very helpful in providing the possibility of the transfer of viral infection through surfaces [4].

There are many reported studies regarding the transfer of microbes from the surfaces or hands onto other viruses, but the studies related to the interaction of SARS-CoV-2 between the human hand and the surfaces are very rare. The evidence from the previous studies showed that the transfer of viral fraction on the fomites is not only dependent on the type of surface and humidity but also...
depends on the viral species [5]. One of the studies showed that SARS-CoV-2 viral RNA levels were observed to be very less on the environment than that of the person’s nasopharyngeal sample which indicates that only a portion of viruses that were shed through the droplets goes to the surfaces [6,7]. The reports on environmental studies confirm that the transfer of microbes from hands to surfaces is possible, likely through bacteriophages, MS2, fr and φX174 which can be transferred from gloves to glass. But then the transfer of microbes was reduced through hand washing and by washing the hands, it removes the sebum, sweat and microorganisms from hands by changing the skin characteristics [8]. On the other hand, it is very unclear from the study how the characteristics of skin impact the transfer of virus. So, further studies are necessary to determine the effect of hand washing that prevents the transfer of SARS-CoV-2. The efficiency of hand washing based on the skin characteristics like hydrophobicity/hydrophilicity, increasing/decreasing the pH has to be addressed. And also it is very important to examine the effect of hand washing that prevents the transfer of SARS-CoV-2 to prove the transfer efficiency [9,10].

2. Different variants of the virus

The Coronaviridae family such as SARS-CoV-2 is a member of the β-CoV genus and it is similar to the MERS-CoV, SARS-CoV and other human coronaviruses in terms of genetics and its taxonomy [11]. Recently, the newly emerged threat is that there are ‘relatives’ of SARS-CoV-2 which should be taken into account because of the availability of very limited data (figure 1). So, previous researches should be taken into consideration to know about the preventive measures taken to destroy the viral outbreak [12]. The taxonomy and genetics of new viral outbreaks are very important to study, because they play a major role in the development of new approaches against the virus [13]. Therefore, the coronaviruses carry the encapsulated RNA and positive strands which are delivered into the host and through that means it starts infecting the person [14].

The host cell and the interactions of viruses are through the surface proteins which play an important role in examining the different range of coronaviruses. In addition, the viral attachment to the non-living surfaces also needs to be studied to understand the structure of coronavirus to determine the attachment mechanism. Moreover, the current SARS-CoV-2 carries different structure which contains different proteins in the structure such as glycoprotein (GP), haemagglutinin esterase (HE), envelope protein (EP), spike protein (SP), nucleocapsid protein (NP) [15]. They are present inside the lipid layer and followed by the viral RNA and protect these proteins. Though the role of those proteins is not fully studied but GP was the only protein which is detected frequently on the viral surface. The GP is the main component of the virus that gives the shape of the coronavirus membrane and also is responsible for the virus cell-binding interactions. On the other hand, the EP was found in very small quantities and they are responsible for the release of viral contents [16]. The previous studies suggest that the ion channel action on the EP is necessary for the disease progression related to the pathology. Lastly, it is very tough to exaggerate the significance of SP, HE and the cell-binding mechanism of the coronaviruses [17,18]. In some studies, it is mentioned that SP proteins are the fusion proteins responsible for the attachment to the host cell receptors. The coronavirus interacts with the host cells which is identified by that the cell and is formed through the presence of enzymes. The SP of the SARS-CoV-2 were identified by the enzyme TMPRSS2 on the cell wall which is an attachment to the ACE2 (angiotensin-converting enzyme 2) receptor. This ACE2 receptor of the cell is formed by the SP of the coronavirus and this is solely responsible to initiate the entry into the host cell (figure 2). In another study, it has been reported that HE is also an important protein in the host cell entry mechanism, and it plays an important role in improving and enhancing the SP functions by permitting the virus through the mucosal tissue [19,20]. The novel SARS-CoV-2 is developing the mutations very rapidly and also it transmits the virus very quickly to the host cells. There is significant chance of the antibodies becoming ineffective because they fail in preventing the attack of virus to the host cell. So, the spiked proteins that is the ‘S’ proteins keeps evolving and leads to exaggerated action towards the host cells. The new variant for transmission of the SARS-CoV-2 is the gamma variant (P.1). This viral network states that the N501Y, E484 K and K417N which is the receptor building domain of SP to intensify its attraction to human receptors. This gamma variant tends to escape from immune responses of the body and with the mutation this virus becomes more contagious than the previous strains. Another variant which has very high transmission rate is the delta variant AY.1, AY.2. This viral network states the hyper local outbreaks which mean the SP of the coronavirus aggravates its affinity towards the human cells. Therefore, vaccination is the best defence mechanism to battle against the fast moving Delta variant [19,20].

3. Reasons for COVID spread

3.1. Contaminated surfaces

In a study, researchers have used a stochastic-mechanistic approach to evaluate the risk of infection from a single, hand to surface and hand to face contact. The infection risks were evaluated based on the SARS-CoV-2 samples which are detectable and quantifiable. It was assumed that the conversion of SARS-CoV-2 RNA to the viral infection follows a uniform distribution [21]. The range of 100–1000/infective virus was estimated using the plaque-forming units (PFU). The SARS-CoV-2 virus data from the enclosed RNA viruses are influenza A (H1N1), A (H3N2) and influenza B which have different ratios of gene copies per TCID50. The variance
in the decay rate on the surface of the infective virus was compared with the decay ratio of the viral RNA. The viral transmission from surface to hand and from hand to mucus membranes was expected to be relative to the concentration of infective virus on the surfaces and its efficiency of transfer in both boundaries. The probability of infection \( P_{\text{inf}} \) of a dose was evaluated using the dose–response model [22]. This is based on the studies reported based on SARS-CoV and MHV-1 (murine hepatitis virus) infection in mice. The higher limit of the dose–response curve is reliable with the two different variants of SARS-CoV-2 in hamsters, ferrets and mice and they exhibited 100% infections with a dose of 105 TCID50. Figure 3 shows that the SARS-CoV-2 infection from the fomite surface contact was low, and it is inclined to show that the infection rate is prevalent in the community settings. The infection risk from the single surface to hand contact followed by the hand to face contact with the contaminated fomites is related to the surface contamination of about 0.01 RNA genome copies with \( 10^{-9} \) surfaces [24].

### 3.2. Surface-mediated community transmission

The spread of SARS-CoV-2 was also from the contaminated surfaces in the public spaces (e.g. trains, buses, buttons, light buttons, etc.). These risks were also estimated by the prevalence of disease in the community and its frequency in contact with the surface. This model will explain the possibility of infection to the people when they contact the surface for about 7 days [25]. The surface inoculum present in this model is described as the infected people use their hands to protect the mouth during coughing and then again touch the infected surface. Then they have also considered the saliva/sputum as the viral load samples of the infected patients showing symptoms of the first 14 days [26]. The saliva/sputum concentrations of SARS-CoV-2 samples were estimated in the genome copies and the TCID50 concentrations. The frequency of contaminated surface was evaluated by the disease prevalence in the community and also through the frequency of contact with the surface. In this method, two contact frequencies were used and they are analysed for every 1–20 min which is treated as high and every 60–240 min, treated as low. The assumptions made here are that the cough spreads conically with the virus particles. The concentration of viral particles in the sputum, volume of expelled sputum/cough and distance between the hand and the mouth were considered as the virus inoculum on hands [27]. The transfer of viral particles from hand to mucus membrane and surface to hand is proportional to the virus concentration on the surface and both the interfaces. The viral concentration on the contaminated surface exponentially decayed over the period and the decay rate of SARS-CoV-2 on the contaminated surfaces was calculated. Here also, the dose–response model was used to evaluate the probability of infection of virus at a given dose. The viral concentration on the contaminated surface was reduced exponentially according to the log10 values based on hand sanitizers and surface disinfection [28]. Hand washing is not considered in this model, whereas alcohol-based hand sanitizers were considered and selected for the hand disinfection due to their extensive availability and convenience of usage [29]. They have assumed that hand sanitizers are similar to the hand washing method which helps in the reduction of SARS-CoV-2 on hands. They have also used Monte Carlo simulations to measure the variability and uncertainty of the input parameters. In addition, they also incorporated five times simulations and all the models were simulated for about 50,000 times. The estimations include time, frequency and exposure of contamination for 7 days (figure 4). The values were recorded and the average values of all the simulations are also reported [30,31].

Hand hygiene was considered as the most important intervention for reducing the risk of SARS-CoV-2 infection. The researchers have taken high and low compliance data from hand to mucus membrane and surface to hand is proportional to the virus concentration on the surface and both the interfaces. The viral concentration on the contaminated surface exponentially decayed over the period and the decay rate of SARS-CoV-2 on the contaminated surfaces was calculated. Here also, the dose–response model was used to evaluate the probability of infection of virus at a given dose. The viral concentration on the contaminated surface was reduced exponentially according to the log10 values based on hand sanitizers and surface disinfection [28]. Hand washing is not considered in this model, whereas alcohol-based hand sanitizers were considered and selected for the hand disinfection due to their extensive availability and convenience of usage [29]. They have assumed that hand sanitizers are similar to the hand washing method which helps in the reduction of SARS-CoV-2 on hands. They have also used Monte Carlo simulations to measure the variability and uncertainty of the input parameters. In addition, they also incorporated five times simulations and all the models were simulated for about 50,000 times. The estimations include time, frequency and exposure of contamination for 7 days (figure 4). The values were recorded and the average values of all the simulations are also reported [30,31].

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of about 1 in 4 people using hand sanitizers and 3 in 4 people disinfecting the hands when they contact the fomites surface. The risks of SARS-CoV-2 transmission through fomites were evaluated as low compared to the community infection rates [32]. During the high prevalence rate, the fomites risk becomes non-negligible because the high risks were due to the droplet transmission routes. Though, the single touch risks were considered to be very low because the person’s infection increases when the individual contacts dozens of objects and frequently contacted objects in the city every hour (e.g. ATMs, railings, cross walks, buttons and public transportation). So every interaction will lead to the transmission of coronavirus. On the other hand, if we assume that the people contact the surface around 10 times/day, he/she has the same probability of the infection risk with a 1% prevalence rate \(7 \times 10^{-6}\) [33,34].

In these models, they have also included mask interventions because of the fomite-mediated transmission along with the hand disinfection and surface disinfection. Masks shown to be effective in the transmission of SARS-CoV-2 virus by limiting the aerosol droplets exposure but it also induces the fomite-mediated transmission. There are also insufficient data in using the masks as the effective way to reduce transmission of droplets and the frequency of hand to mouth contacts. So, the usage of masks cannot be used as an intervention for the reduction of transmission. There are limitations in the dose–response model because it is based on only the SARS-CoV-2 and MHV-1 infection in mice. The viral entry to the host through fomite transmission is very much smaller than the intranasal administration of the virus. Moreover, they have extrapolated the model from mice to people from MHV-1 and SARS-CoV to SARS-CoV-2 [35,36]. The other limitations are dose–response relationship that was determined and measured in PFUs and for them genome copies are needed. The model parameters used for the transfer of virus and the decay rates were tested experimentally in the laboratory and in the different environmental conditions. The prevalence rate is directly
proportional to the people who are infected and the surface contact. The infected persons would be staying at home, quarantine or isolation and they will not cough directly on the hand. In this situation, the risks are higher than the stated community infection rates [37].

With all these limitations, the above-mentioned models were considered as a very valuable tool to know and distinguish the risks of surface-mediated transmission of SARS-CoV-2 in the community and test its effectiveness. The epidemiological investigations, randomized trials are not feasible for the fomite-mediated transmission because they are considered as a rare event and difficult to differentiate from the other transmission routes. The results obtained from these models are considered as the supporting evidence for the fomite transmission of SARS-CoV-2, and it is useful for the possible intervention strategies [38].

4. Points from a global perspective

Though there are only limited shreds of evidence indicating the infection risk is lower for the fomites and these fomites are not likely taken as consideration for the major transmission pathways for the coronavirus infection. Nevertheless, SARS-CoV-2 RNA has been found in the hospital rooms, community settings, quarantine rooms, and there also occurs a chance of SARS-CoV-2 infection even after the disinfection which can occur through cross-contamination [39]. Moreover, the new variants of SARS-CoV-2 with the potential of very high transmission rates continue to emerge as they are behaving very differently on the surfaces than the strains which have been studied previously [40]. So, it is very important to follow and monitor the various control measures in order to break the chain of infection/transmission of all possible ways like including proper hand hygiene, appropriate cleaning, disinfection and multilayered mask [41]. Many researchers have suggested improved design strategies for increasing and improving the quality of airflow in the respirators [42,43]. The evidence from the reported studies put forward that the droplet transmission and the aerosol transmission as the primary transmission of SARS-CoV-2 virus. Public health messaging shall highlight the safe and effective use of disinfection products to prevent acute and chronic health effects [44]. Therefore, the clear public health message which accounts for these uncertainties will help to gain public confidence and support public health efforts. In a recent study in The Lancet, analysis shows that only 104 (57%) of 182 countries had the functional capabilities to perform crucial activities at national and subnational levels. As low as 18% of the countries showed low readiness and would require external resources to control an emerging infectious disease event [45]. Further epidemiological research is very important and urgently required to understand the behaviour of different strains of coronavirus to come up with stronger protocols to fight back this pandemic [46,47]. Many respiratory viruses will remain active for many days as long as they are stored in aqueous solutions at relatively low temperatures. SARS-CoV-2, for example, stored in a medium in a sealed tube exhibited a half-life of 11, 4, 1.3 and 1.2 days when stored at 5, 13, 21 and 25°C, respectively [48]. Viruses in the aerosol may have a much shorter half-life. One experiment performed at 23°C reported a half-life of 1.1 and 1.2 h for SARS-CoV-1 and SARS-CoV-2, respectively [35]. SARS-CoV-2 is available in liquids, so the deposition of viruses on surfaces of different materials in the laboratory experiments is straightforward: a droplet containing a certain amount of viruses is placed on the surface, and the substrate is kept at controlled conditions, in particular temperature and air humidity. In practical cases, however, the viruses are spreading through aerosols formed predominantly by coughing and sneezing. The liquid droplets are distributed over a broad range of volumes. If a person wears a mask properly, a good majority of droplets will be captured by filters. In other cases, droplets will be released into the surrounding air and follow the rules of hydrodynamics; they will be falling due to the gravitation, but sedimentation speed will depend on their size.

5. The role of surfaces

Small objects like viruses levitate in the air and are moved together with the surrounding gas by winds, so they are unlikely to touch the surface of any material. However, respiratory viruses in the air are likely to be found in water droplets much larger than viruses themselves. The lifetime of droplets in the air depends on evaporation. The evaporation of water molecules from a water droplet levitating in the air depends on the air temperature and relative humidity. The water droplets evaporate faster at high temperatures and low relative humidity, feel the gravitational force which favours falling; falling is faster for larger water droplets. According to Holltermann [49], the sedimentation velocity of a water droplet of diameter 100 µm is about 0.2 m s\(^{-1}\), for droplets of 10 µm, it is 3 mm s\(^{-1}\), while for droplets of diameter below about 1 µm it is below µm s\(^{-1}\). Tiny droplets will therefore need several days to drop from 1 m height to the surface. Small droplets levitating in the air of moderate humidity will dry well before touching any surface. The dynamics of water droplet evaporation is complex [50] but could be simplified for the air of relative humidity up to about 90%. For example, Hollermann [49] calculated the lifetime of sedimenting water droplets in a range of relative humidities and air temperatures. The lifetime of 100 µm droplets at relative humidity 50% and room temperature was about 20 s. The water droplets, therefore, dry quickly at ambient conditions. The droplet lifetime increases with increasing air humidity. The droplets of diameter 100 µm need a couple of minutes to dry at the relative air humidity of 90%. The lifetime approaches infinity as the relative humidity approaches 100%. All these estimations assumed free-falling of droplets through the air at a constant humidity, neglecting the influence of evaporation on the relative air humidity in the vicinity of a droplet. The assumption is justified in many practical cases.

Unless evaporated before touching the surface, a reasonable-size water droplet containing viruses adheres to the surface of any solid material. Once on the surface, the water molecules evaporate from the water droplet at a rate that depends on the surface temperature and the relative humidity of the surrounding air. The assumptions in the previous paragraph are not valid for the case of steady droplets on a surface of a solid material since the velocity of a droplet sitting on a surface is zero. As a consequence, a sheath of high-humidity air forms around a water droplet on the
surface. The assumptions made in the previous paragraph are acceptable only if the air of reasonable humidity moves along the surface. Otherwise, the removal of water vapour is governed by water vapour diffusion, which is a very slow process. Therefore, the water droplets remain on the surface for an appreciable time, providing the surrounding air does not move. The interaction of a water droplet with solid material depends enormously on the surface properties. The water droplet on the surface of highly hydrophobic materials will remain almost spherical, as shown in figure 5a. However, on the surface of a hydrophilic material, the water droplet will spread on the surface, so the surface area between the water droplet and surrounding air will be larger, as shown in figure 5b. In a particular case of a super-hydrophilic surface finish, the water droplet will spread on a large surface, as shown in figure 5c. Once the droplet touches the surface of a super-hydrophilic material, it starts spreading because of capillary forces and finally occupies a large surface area. In the limited case, the water droplet will assume an infinite surface. Such a huge surface favours evaporation, so in the limited case of the infinite surface area of the water droplet on the super-hydrophilic surface, the evaporation time will be extremely short so that a virus will dehydrate quickly.

Unfortunately, the role of dehydration on the virus inactivation has not been studied in detail by many authors. For example, Kratzel et al. [51] reported a decline of the 50% tissue culture infectious dose per millilitre for over 100-times after 1 h of drying on a metallic substrate. However, after the initial loss of infectivity, the recovered virus titres remained stable over the next few hours, with only a minimal decline. Such extremely nonlinear effects are yet to be studied by various groups to enable insight into the complex inactivation mechanisms upon drying as triggered by Kratzel et al. [51].

Interaction of a water droplet with the highly hydrophobic porous material is the same as shown in figure 5a: the droplet remains in the almost perfectly spherical form, thus minimizing the surface-to-volume ratio. Contrarily, when a water droplet touches the surface of a highly hydrophilic porous material, it is pulled into the pores, as shown in figure 5d. Any virus present in the original water droplet will be embedded inside the porous structure and remain active unless the material is virucidal or coated with a virucidal coating. The coating may be very thin since the concentration of viruses in the water droplets is small. According to the above discussion, the half-time of viruses on the surface of different materials should depend on the surface energy of a solid material. The evaporation of water is fastest on the surface of non-porous super-hydrophilic materials. Such materials do not exist in nature but could be made in laboratories [52]. The super-hydrophilic surface finish is thermodynamically unstable, so hydrophobic recovery is observed. The recovery time depends on numerous parameters, including re-orientation of polar surface functional groups and adsorption of any impurities [53]. The evaporation of water droplets on the surface of highly hydrophobic materials should be much slower since the spherical geometry of a water droplet (figure 5a) ensures minimal surface-to-volume ratio. The evaporation can be accelerated by blowing air of low humidity onto the surface, similar to hair-drying. In such a case, the water droplet evaporates at a rate similar to sedimenting water droplets, in a minute or so, depending on the droplet size, the relative humidity and the speed of the air. A droplet soaked in a highly hydrophilic porous material (figure 5d) does not evaporate in a reasonable time since the airflow will not be effective enough to remove the water vapour within the pores. From this perspective and considering the observations reported by Kwang et al. [48] about the long half-life of viruses in liquids, the viruses remain active in porous materials much longer than on smooth surfaces.

Numerous authors studied the stability of SARS-CoV-2 on surfaces. The experiments in the real environment (i.e. coughing and/or sneezing) are impractical and it is impossible to keep parameters under control. Hence, all authors performed experiments in laboratories at highly controllable conditions. All authors deposited droplets of virus-contaminated liquids on surfaces of different materials and monitored the inactivation kinetics. A few groups reported the half-time of SARS-CoV-2 on various surfaces [48,54–56]. Some also reported the pre-treatment details, such as sterilization technique, cleaning procedure, etc. None, however, reported the hydrophilicity of the substrates, so the variation of the virus inactivation versus the surface free energy is yet to be investigated.

Figure 6 shows the half-life of SARS-CoV-2 on surfaces of various materials. Figure 6a summarizes results versus the temperature of substrates, which is typically the same as the surrounding air temperature. Namely, all experiments were performed at highly controllable conditions with temperature variations less than 1°C. Figure 6b shows the half-life versus the relative humidity of the surrounding air. The humidities between 20 and 80% were tackled. No author reported a possible change of the relative humidity due to the evaporation of the liquid from the surface. The half-life is of the order of an hour, so the water likely evaporated during the experiment.

The results summarized in figure 6 show a significant scattering of measured points, but the trend is evident: the half-life depends more on the temperature than any other parameter, such as the type of material used as a substrate. This result clearly shows that temperature-stimulated inactivation is more likely than any interaction of viruses with a solid material. The observation will be discussed later in this paper.

Focusing on particular materials, the half-life for stainless steel, glass, plastics and fabrics is shown in figures 7–10,
respectively. Figure 7a represents the correlation between the SARS-CoV-2 half-life and the stainless steel temperature. The half-life decreases with increasing temperature. At the temperature of 5°C it is as long as 3 days. The observation is in accord with the general knowledge about the self-induced inactivation of viruses: the inactivation rate (reciprocal value of the half-life) increases exponentially with the temperature since the chemical reactions increase with increasing temperature. Deep freezing (for example, at −80°C) makes the virus half-life approach infinity. The half-life at room temperature is about 10 h, meaning that a significant amount of viruses remain active for several days. Interesting is the behaviour of the half-life as a function of relative humidity. The results for stainless steel are summarized in figure 7b. The results are scattered significantly, so drawing any correlation would be speculation. According to the above discussion about water evaporation from the surface of non-porous materials, the half-life should increase with increasing humidity since the evaporation rate decreases with increasing humidity, at least for the limiting case of humidity approaching 100%. The results in figure 7b do not support this hypothesis. One possible explanation could be the persistence of a water droplet well after the virus half-life time. Unfortunately, the authors have not reported the dryness of the samples when measuring the SARS-CoV-2 viability.

The half-life of SARS-CoV-2 on a glass surface is shown in figure 8. Not all cited authors probed this material, so there are fewer points in figure 8 than in figure 7. The results are similar to those for stainless steel. We show them just for the sake of completeness of this paper. Again, the temperature dependence is significant, indicating the self-inactivation rather than the interaction of viruses with the glass substrate. In fact, glass is regarded as a chemically inert material, so it is unlikely that any chemical interaction with the viruses could occur. The same applies to plastics (figure 9). Here, it is worth stressing that not all authors reported the exact composition of plastics. For example, Kwon et al. [48] used pure polypropylene, while Doremalen et al. [35] did not specify the composition of plastics used in their experiments. Several authors also probed textiles for the survival of SARS-CoV-2. Unfortunately, the authors did not report about the water droplet protruding into the material, but cotton is renowned for rapid wetting. The half-life on such porous material of moderate hydrophilicity is shown in figure 10. There is no significant difference compared to other materials (figures 6–9), so it is possible to conclude that there is no chemical interaction that could facilitate the virus’s inactivation on fabrics.

The observations of figures 6–9 implicitly indicate very little (if any at all) interaction of SARS-CoV-2 with the surfaces since the measured values are scattered, and no statistically significant dependence on the type of material could be observed. The results summarized in this paper are significantly different from the classical work of Tiwari et al. They reported the survival of two avian respiratory viruses on porous and non-porous surfaces almost 15 years ago [57]. Namely, Tiwari et al. found the survival of the
avian metapneumovirus and avian influenza virus on non-porous material surfaces (e.g. stainless steel, plastic, latex and glass) higher than those on porous material surfaces (e.g. paper and cotton). Furthermore, they found that these porous surfaces have the ability to capture viruses in their matrix and dehumidify them while accelerating the destruction process of envelopes, thus making the virus less infectious. The discrepancy between Tiwari’s paper and the results summarized in this review may be attributed to different structures of the viruses studied. A trivial explanation would involve differences in experimental setups.

Here, it is worth mentioning the surface purity. Any chemical interaction between a virus and the surface of specific functionality will be possible only if the surface of the solid material is free from impurities. Metals, particularly those of high effective surface, including nanoparticles, are renowned for germicidal properties [58]. They are, however, also known for rapid passivization upon ambient conditions. Most metals will assume a thin oxide film. Furthermore, they are renowned for attracting organic gaseous impurities. Surface-sensitive techniques for material characterization like Auger electron spectroscopy, X-ray photoelectron...
spectroscopy and secondary ion mass spectrometry can detect a significant concentration of carbon, usually in the form of hydrocarbons which stick onto the surface to form about a monolayer-thick chemisorbed film. Such a film cannot be removed simply by evacuation to ultra-high vacuum conditions typical for the surface-sensitive techniques. The surface morphology, structure and composition are particularly complex for alloys. Surface impurities will suppress any interaction of viruses with the solid material. From this point of view, the half-life of SARS-CoV-2 would be similar for all materials capable of chemisorption of organic impurities and similar to stable polymers composed of hydrogenated carbon materials. Such a conclusion could be drawn based on results summarized in figure 6.

Here, it is worth mentioning that different materials behave differently in terms of adsorbing any gaseous impurities. For example, polyolefins [53] and fluorinated polymers [59] exhibit almost theoretical composition when probed by highly sensitive techniques for surface characterization. The other extreme are freshly deposited metallic films known as getters—i.e. materials likely to bond any gaseous molecules on their surfaces [60]. Thus, any pure metallic surface will irreversibly absorb gaseous molecules, thus hindering the original surface composition.

The surface is rarely perfectly smooth. Roughness on the nanometre scale is a standard feature. The roughness will increase the actual surface well above the geometric value. The large surface will further increase the capability of bonding gaseous impurities and thus contribute to the complexity of the interaction with viruses. Little work, however, was reported on the influence of the surface morphology on virus inactivation. From this point of view, it should be stressed that many materials used nowadays or proposed to be used in the future in highly efficient masks [61] are based on results summarized in figure 6. The results summarized in this paper call for an innovative surface finish of materials to favour chemical interaction with viruses. As mentioned above, materials like metals, metal oxides, ceramics and glass are not virucidal because they are capable of chemisorption of organic impurities. The organic impurities from ambient air will screen any interaction with the substrate. From this point of view, polymers should perform better. Namely, many polymers do not bond organic impurities. The most promising should be the polymers with positively charged surfaces, like those with a large concentration of amino groups on the surface. Namely, amino groups make the polymer surface positively charged so that it can attract viruses with a negative surface charge like SARS-CoV-2 [66]. It was reported that amino acid-based supramolecular polymer hydrogels boast intrinsic antibacterial activity [67]. The grafting of non-woven cellulose fabrics with amino groups resulted in excellent germicidal properties for bacteria E. faecalis [68]. Amino cellulose derivates could be prepared by wet chemical methods, and such surfaces exhibit antibacterial activity for numerous bacteria [69]. Probably the most straightforward technique for grafting amino groups on a polymer surface is using flowing afterglow of ammonia plasma [70]. The method is illustrated in figure 11. Ammonia is passed through a discharge chamber where a weakly ionized gaseous plasma is sustained by an electrical discharge. The NH₃ molecules dissociate upon plasma conditions and form radicals such as N, NH, NH₂ and H. The H and N radicals tend to associate and form hydrogen and nitrogen molecules, respectively. However, the NH and NH₂ radicals remain stable for an appreciable time (depending on the gas pressure) and interact chemically with a polymer surface by replacing the hydrogen atom in the C–H bond. Hence, they form the amino group (C–NH₂). The amino groups are relatively stable on the polymer surface [70]. The treatment time necessary for saturating polymers with amino groups seems to be a few seconds only [70]. Such a surface finish enables the formation of excessive positive charge on the polymer surface, which has been proven as efficient for irreversible chemical modification of some viruses [71].

An alternative to grafting amino groups on polymer surfaces by a brief treatment with NH and/or NH₂ radicals is the deposition of a virucidal coating. As early as 2010, Wong et al. [72] reported excellent bactericidal and virucidal efficiency of ultrathin films assembled layer by layer from polycationic N-alkylated polyethylenimine and polyalanine. The films were deposited on silicon substrates. The substrates were first exposed to non-equilibrium oxygen plasma to remove any organic impurities and activate (increase the surface free energy) the surface for better adhesion of the coating. Coatings of various thicknesses between about 10 and 100 nm were prepared and tested for germicidal efficiency. The antibacterial activity was explained by the existence of positive charges on the surface, which were available to interact with bacterial cell membranes. The coatings were also tested against influenza A/WSN/33 (H1N1)

6. Artificial antiviral surface and coatings

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virus. This virus has an outer lipid envelope that was vulnerable to the high density of positive charges on the surface of the coatings. The virucidal activity of a very thin coating was not as good as the bactericidal but improved with increasing coating thickness. The authors explained the incomplete virucidal activity of very thin films by the existence of voids on the surface. The voids were supposed to be large enough to fit a virus but too small for a bacterium. The films were tested for mechanical and microbial durability, and no significant ageing was observed. The coatings were found to be non-cytotoxic to a mammalian cell line based on cell viability assay. It can be deduced that the solution provided by Wong et al. [72] is applicable to any non-porous material providing the surface is first activated to ensure the appropriate adhesion of the polycationic N-alkylated polyethyleneimine. Although the authors have not mentioned it, these coatings are probably not suitable to be deposited within the pores of porous materials such as textiles. The schematic of Wong’s technique is presented in figure 12.

A somewhat different but effective approach was adopted by Tuladhar et al. [73]. They immobilized quaternary ammonium compounds on glass and plastic surfaces and tested the virucidal activity against enveloped influenza A (H1N1) virus and non-enveloped poliovirus Sabin1. Interesting enough, the virucidal effect against the influenza virus was found within 2 min only after applying the virus, while no virucidal effect against poliovirus was found in 6 h. The viruses were dispersed and spread on the substrates, thus mimicking coughing and sneezing. The authors attributed the fast decay of the enveloped virus to drying, followed by chemical interaction. Without coating (i.e. on pristine surfaces), the enveloped respiratory viruses remained infective for 5 and 10 days for glass and plastic, respectively. The effect of the coating was, therefore, dramatic since the inactivation period shrank roughly 10,000 times! According to Tuladhar et al., the virucidal mechanism of quaternary ammonium compounds on enveloped viruses probably involved disruption or detachment of the viral envelope.

Mostaghimi et al. [74] deposited coatings of copper alloys on various substrates and demonstrated higher antibacterial properties compared to the conventionally manufactured sheets. They attributed the antibacterial properties of such coatings to the microstructure. They reported a correlation between biocidal effectiveness and copper content in the alloys. Such coatings were tested for several months in real-life conditions at two hospitals. They proved that the coatings provided long-lasting, durable and low-maintenance surfaces with strong antibacterial properties. Unfortunately, no experiments with viruses were performed using this technique.

Park et al. [75] evaluated the virucidal efficiency of fluorinated titanium dioxide coatings on human norovirus and a few surrogates. They used a typical fluorescent lamp as a source of radiation in the visible and near-ultraviolet range and monitored the destruction of RNA and capsid oxidation versus treatment time. They reported rapid destruction of norovirus surrogates at about 2- to 3-log reduction within an hour. Infectivity reductions on pure TiO2 coatings using the same lamp and other conditions were marginal. Under realistic room lighting conditions, MS2 infectivity declined below the lower detection limit after about 12 h. The authors found that the capsid protein oxidation had a significant effect on infectivity loss. The oxidation was due to the photocatalytic production of cytotoxic reactive oxygen species stimulated by fluorine. Decreasing the wavelength of light upon irradiation of photocatalytic materials increases the virucidal efficiency. Indeed, wavelengths in the range of germicidal wavelengths (below about 300 nm) also cause direct degradation of viruses. The method was recently elaborated for SARS-CoV-2 by Gidari et al. [56]. They used standard radiation at 254 nm. UV-C light induces chemical modifications of nucleic acids, leading to the blocking of replication mechanisms. SARS-CoV-2 was found to be highly susceptible to UV-C irradiation since a 3-log reduction was observed in a minute or so. Surprisingly enough, statistically significant differences were observed for different materials. The fastest decay was observed for glass (SARS-CoV-2 titre below the detection limit in 20 s) and the slowest for polymer. It is not easy to interpret these results. In any case, large doses of UV-C radiation used by Gidari et al. [56] (the order was 100 J m⁻²) make this technique impractical. Furthermore, UV radiation is harmful to humans and often causes irreversible surface modifications of polymers.

7. Limitations, conclusion and future directions

7.1. Limitations and conclusions

This review has several limitations. Firstly, due to operational limitations during an outbreak, the number of patients, surfaces and times tested is relatively small, and larger studies are to be reported to confirm our observations. The selection of patients in almost all studies were random and a positive RT-PCR test is the only confirmation factor for SARS-CoV-2 virus. There is no statistically significant difference in SARS-
CoV-2 half-times for different materials. Obviously, the virus does not interact with the surfaces probed by authors whose results are summarized in figure 6. So, there is a need to develop anti-SARS-CoV-2 surfaces of good durability, as was done 10 years ago for some other viruses. The positively charged surfaces performed best, and perhaps the most useful technique is grafting polymers with amino groups using brief plasma treatment. We are already following physical distancing, lockdowns, mask use and restrictions of movement for controlling this virus. However, our scientific understanding of the virus’s effective control is still limited even after more than one year of the pandemic, and additional research is necessary to combat emerging COVID-19 transmission vehicles that are currently not known.

7.2. Future directions
The future directions of scientific research on the inactivation of respiratory viruses can be deduced from the reported observations. First, the inactivation by drying should be elaborated. Such experiments are difficult to conduct since many materials bond a substantial amount of water, so the experimental conditions should be controlled carefully. Vacuum drying is among the most efficient non-invasive techniques. Once the inactivation mechanisms by drying are elaborated, scientists should tackle the influence of various surface functional groups on the stability of SARS-CoV-2. Amino groups have already been proven as efficient inactivators of a few types of respiratory viruses, but there may be more effective surface finishes. The surface functional groups may not be stable under ambient conditions, so the development of methods for rapid functionalization of surfaces likely to act as virus inactivators will have to be tackled, too.

References

1. Leung NHL. 2021 Transmissibility and transmission of respiratory viruses. Nat. Rev. Microbiol.
2. Riediker M, Tsai D-H. 2020 Estimation of viral aerosol emissions from simulated individuals with asymptomatic to moderate coronavirus disease. JAMA Netw. open 3, e2013807. (doi:10.1001/jamanetworkopen.2020.13807)
3. Dhand R, Li J. 2020 Coughs and sneezes: their role in transmission of viral respiratory infections, including SARS-CoV-2. Am. J. Respir. Crit. Care Med. 202, 651–659. (doi:10.1164/rccm.202004-1263PP)
4. Choi H, Chatterjee P, Coppin JD, Martel JA, Hwang M, Jinadatha C, Sharma VK. 2021 Current understanding of the surface contamination and contact transmission of SARS-CoV-2 in healthcare settings. Environ. Chem. Lett. 1–10.
5. Pittal AK, Bischel HH, Kohn T, Julian TR. 2017 Virus transfer at the skin-liquid interface. Environ. Sci. Technol. 51, 14417–14425. (doi:10.1021/acs.est.7b04949)
6. Azimi P, Keshavarz Z, Laurent JGC, Stephens B, Allen JG. 2021 Mechanistic transmission modeling of COVID-19 on the Diamond Princess cruise ship demonstrates the importance of aerosol transmission. Proc. Natl Acad. Sci. USA 118. (doi:10.1073/pnas.201482118)
7. Jones RM. 2020 Relative contributions of transmission routes for COVID-19 among healthcare personnel providing patient care. J. Occup. Environ. Hyg. 17, 408–415. (doi:10.1080/15459624.2020.1784427)
8. Pastorino B, Touret F, Gilles M, de Lamballerie X, Charrel R. 2020 Prolonged viability of SARS-CoV-2 in fomites.
9. Colaneri M et al. 2020 Severe acute respiratory syndrome coronavirus 2 RNA contamination of inanimate surfaces and virus viability in a health care emergency unit. Clin. Microbiol. Infect. 26, 1094. (doi:10.1016/j.cmi.2020.05.009)
10. Moore G et al. 2021 Detection of SARS-CoV-2 within the healthcare environment: a multi-centre study conducted during the first wave of the COVID-19 outbreak in England. J. Hosp. Infect. 108, 189–196. (doi:10.1016/j.jhin.2020.11.024)
11. Adhikari U et al. 2019 A case study evaluating the risk of infection from Middle Eastern respiratory syndrome coronavirus (MERS-CoV) in a hospital setting through bioaerosols. Risk Anal. 39, 2608–2624. (doi:10.1111/risa.13389)
12. Jiang X-L et al. 2020 Transmission potential of asymptomatic and paucisymptomatic severe acute respiratory syndrome coronavirus 2 infections: a 3-family cluster study in China. J. Infect. Dis. 221, 1948–1952. (doi:10.1093/infdis/jiaa206)
13. Thanayil A, Rajakumari R, Kumar A, Choudhary MD, Palit P, Thomas S. 2021 New insights into application of nanoparticles in the diagnosis and screening of novel coronavirus (SARS-CoV-2). Emergent Mater. 4, 1–17. (doi:10.1007/s42247-021-00182-w)
14. Cevik M, Tate M, Lloyd O, Maraolo AE, Schafers J, Ho A. 2020 SARS-CoV-2, SARS-CoV, and MERS-CoV viral load dynamics, duration of viral shedding, and infectiousness: a systematic review and meta-analysis. The Lancet Microbe.
15. Kang S et al. 2020 Crystal structure of SARS-CoV-2 nucleocapsid protein RNA binding domain reveals potential unique drug targeting sites. Acta Pharm. Sin. B 10, 1228–1238. (doi:10.1016/j.apsb.2020.04.009)
16. Nuccielli M, Pieri M, Giono F, Sarubbi S, Cotti M, Andreoni M, Bernardini S. 2021 Evaluation of a new simultaneous anti-SARS-CoV-2 IgA, IgM and IgG screening automated assay based on native inactivated virus. Int. Immunopharmacol. 92, 107330. (doi:10.1016/j.intimp.2020.107330)
17. Calisti R. 2020 SARS-CoV-2: exposure to high external doses as determinants of higher viral loads and of increased risk for COVID-19. A systematic review of the literature. Epidemiol. Prev. 44, 152–159.
18. Walsh RA et al. 2020 SARS-CoV-2 detection, viral load and infectivity over the course of an infection. J. Infect. 81, 357–371. (doi:10.1016/j.jinf.2020.06.067)
19. Ortiz ME et al. 2020 Heterogeneous expression of the SARS-CoV-2 receptor ACE2 in the human respiratory tract. EbioMed. 60, 102976. (doi:10.1016/j.ebiom.2020.102976)
20. Lechien JR et al. 2020 ACE2 & TMRPR52 expressions in head & neck tissues: a systematic review. Head Neck Pathol. 1–11.
21. Bullard J et al. 2020 Predicting infectious severe acute respiratory syndrome coronavirus 2 from diagnostic samples. Clin. Infect. Dis. 71, 2663–2666. (doi:10.1093/cid/ciaa638)
22. Matson MJ, Yinda CK, Seifert SN, Bushmaker T, Fischer RJ, van Doremalen N, Lloyd-Smith JO, Munster VJ. 2020 Effect of environmental conditions on SARS-CoV-2 stability in human nasal mucus and sputum. Emerg. Infect. Dis. 26, 2276–2278. (doi:10.3201/eid2609.202267)
Peršin Z, Mauer U, Pivec T, Mauer T, Vesel A, Mozetič M, Stana-Kleinschek K. 2014 Novel cellulose based materials for safe and efficient wound treatment. Carbohydr. Polym. 100, 55–64. (doi:10.1016/j.carbpol.2013.03.082)

Shokri M, Moradi S, Amini S, Shahlaei M, Seidi F, Saedi S. 2021 A novel amino cellulose derivative using ATRP method: preparation, characterization, and investigation of its antibacterial activity. Bioorg. Chem. 106, 104355. (doi:10.1016/j.bioorg.2020.104355)

Kolar M, Mozetič M, Stana-Kleinschek K, Fröhlich M, Turk B, Vesel A. 2015 Covalent binding of heparin to functionalized PET materials for improved haemocompatibility. Materials 8, 1526–1544. (doi:10.3390/ma8041526)

Hsieh M-S, Chang Y-C, He J-L, Juang R-H. 2019 Positive charge of Arg-201 on hemagglutinin is required for the binding of H6N1 avian influenza virus to its target through a two-step process. Virus Res. 265, 132–137. (doi:10.1016/j.virusres.2019.03.018)

Wong SY, Li Q, Veselinovic J, Kim BS, Klíbanov AM, Hammond PT. 2010 Bactericidal and virucidal ultrathin films assembled layer by layer from polycationic N-alkylated polyethylenimines and polyanions. Biomaterials 31, 4079–4087. (doi:10.1016/j.biomaterials.2010.01.119)

Tuladhar E, de Koning MC, Fundeanu I, Beumer R, Duizer E. 2012 Different virucidal activities of hyperbranched quaternary ammonium coatings on poliovirus and influenza virus. Appl. Environ. Microbiol. 78, 2456–2458. (doi:10.1128/AEM.07738-11)

Mostaghimi J, Pershin L, Salimi-Jazi H, Nejad M, Ringuette M. 2021 Thermal spray copper alloy coatings as potent biocidal and virucidal surfaces. J. Therm. Spray Technol. 30, 25–39. (doi:10.1007/s11666-021-01161-7).

Park GW, Cho M, Cates EL, Lee D, Oh B-T, Vinjé J, Kim J-H. 2014 Fluorinated TiO2 as an ambient light-activated virucidal surface coating material for the control of human norovirus. J. Photochem. Photobiol. B Biol. 140, 315–320. (doi:10.1016/j.jphotobiol.2014.08.009)

Abrahao. 2020.