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The viability of SARS-CoV-2 on solid surfaces

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Abstract

The COVID-19 pandemic had a major impact on life in 2020 and 2021. One method of transmission occurs when the causative virus, SARS-CoV-2, contaminates solids. Understanding and controlling the interaction with solids is thus potentially important for limiting the spread of the disease. We review work that describes the prevalence of the virus on common objects, the longevity of the virus on solids, and surface coatings that are designed to inactivate the virus. Engineered coatings have already succeeded in producing a large reduction in viral infectivity from surfaces. We also review work describing inactivation on facemasks and clothing and discuss probable mechanisms of inactivation of the virus at surfaces.

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COVID-19, SARS-CoV-2, Surface, Coating, Solid, Coronavirus.

Introduction

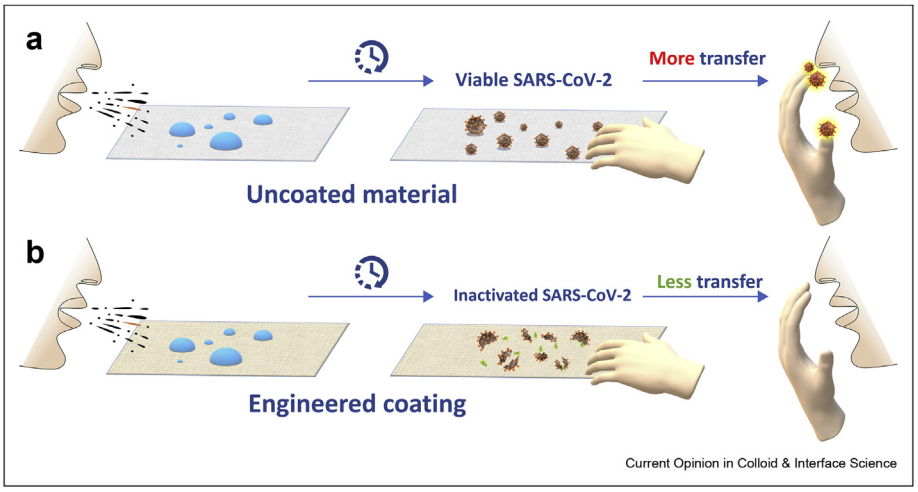
Severe acute respiratory coronavirus-2 (SARS-CoV-2) is the virus that causes COVID-19 and has been responsible for more than 100 million cases and 2 million deaths as of February 2021 (COVID-19 Dashboard by the Center for Systems Science and Engineering at Johns Hopkins University, https://coronavirus.jhu.edu/map.html). SARS-CoV-2 is transmitted through infected respiratory droplets and aerosols generated by a diseased person [1,2]. Respiratory droplets and aerosols can be generated when a person sneezes, coughs, speaks, or breathes [3]. An individual is infected by the virus through nasal or oral inhalation of the infected droplets or aerosols and then attachment of the virus to the epithelial membrane [2]. The pathway to infection is not fully understood but is thought to be via inhalation of either respiratory droplets or aerosolized virus (WHO Transmission of SARS-CoV-2: implications for infection prevention precautions, https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions). For this reason, health officials have advised that individuals should avoid poorly ventilated public places [4], wear a mask in public places, and increase distance between other individuals [3,5].

The possibility of infection via solid surfaces has also been considered. In this scenario, a droplet that contains virus lands on and contaminates an inanimate object. The contaminated object is called a fomite. The next user touches the fomite, and the virus is transferred from the fomite to the user's hand. Infection can occur if the person then touches their nose, mouth, eyes, or ears (Figure 1). A preprint (Behzadinasab et al., medRxiv doi: 10.1101/2021.04.24.21256044) confirmed that SARS-CoV-2 can be transferred from fomites to artificial skin.

A study on Golden Hamsters showed that the virus can be indirectly transmitted through fomites [6], but we are unaware of a study directly showing fomite transmission in humans. The WHO not only states that "fomite transmission is considered a likely mode of transmission for SARS-CoV-2" (WHO Transmission of SARS-CoV-2: implications for infection prevention precautions. https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions), but also notes that "People who come into contact with potentially infectious surfaces often also have close contact with the infectious person, making the distinction between respiratory droplet and fomite transmission difficult to discern" (WHO Transmission of SARS-CoV-2: implications for infection prevention precautions. https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions). Modeling of outbreaks suggests that transmission via fomites may contribute up to 25% of deaths during periods of lockdown [7].

Infection via fomites depends on the longevity of SARS-CoV-2 on a solid because an infectious dose clearly must survive until following users contact the solid. The longevity of SARS-CoV-2 depends on the solid material,

Figure 1



Infection via a fomite. (a) Uncoated material. **(b)** Engineered coating to reduce infection.

but the virus can remain viable on some solids for up to seven days [8,9]. According to the US Center for Disease Control (CDC), one method of reducing fomite transmission is washing of hands (CDC Cleaning and Disinfection for Household, https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/cleaning-disinfection.html). Another method is the disinfection of common-touch objects such as door handles, railings, restaurant tables, and keypads, using disinfectants such as 70% ethanol, bleach, or peroxide (CDC Cleaning and Disinfection for Household, https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/cleaning-disinfection.html). However, these disinfectants do not provide ongoing protection from SARS-CoV-2. A thin film of ethanol evaporates rapidly at room temperature therefore, the solid can be contaminated again within minutes of disinfection. Thus, conventional disinfection does not provide much protection on objects such as a subway handhold where cleaning may only be once per day whereas passengers may touch the handhold within minutes of each other. The labor cost of conventional disinfection is also high. Other methods can also be used to inactivate viable viruses on surfaces, including UV [10], sunlight [11] irradiation, cold plasma [12], and heat [13].

An alternative approach to disinfecting common-touch surfaces, and the main subject of this review, is surfaces that provide a continuous inactivation of the virus. By continuous, we mean that after application, the surface remains capable of inactivating the virus for at least a few weeks. There are two timescales for such an approach: (1) the time to inactivate the virus, which should be as short as possible, preferably minutes, and (2) the longevity of the coating, which should be as long as possible, preferably months or even years. Such a surface can provide protection to users in heavily trafficked areas and preferably at a lower cost because of the lower labor cost.

An important distinction between viruses and bacteria is that viruses do not have a metabolism and cannot reproduce on their own. For this reason, many do not consider viruses to be alive. This is why one does not refer to killing viruses, but rather to inactivating them. An important consequence is that, even when there is no disinfection procedure, the virus loses activity over time; therefore, any effort to inactivate the virus must be viewed against the natural decay of the viral population on the same surface. In this review, we compare the decay of the virus in some control situation without a deliberate disinfection of the surface to the decay on an engineered surface using the following metric:

$$\log \text{reduction} = \text{mean}\left[\log_{10}\left(\frac{\text{Control titer}}{\text{units}}\right)\right] - \text{mean}\left[\log_{10}\left(\frac{\text{Sample titer}}{\text{units}}\right)\right] \quad (1)$$

$$\% \text{ Reduction} = \left(1 - 10^{-\log \text{ reduction}}\right) \times 100\% \qquad (2)$$

where the same units are used for the control and sample titers. For example, the control could be an uncoated solid, and the sample would be a coated solid. The ability of the virus to infect is most commonly quantified by $TCID_{50}$, which is a measure of the dilution required before a sample no longer infects cells. The most commonly used cell is a Vero cell [14,15]. A greater value of $TCID_{50}$ (larger dilution) means that the sample of virus is more potent at infecting the cells.

A logical metric would be the ability to decrease the time required for the virus to reach some threshold level where it cannot infect mammalian cells or has some low probability of infecting cells. To date, however, the infective dose is not known, but less virus is obviously better. In the absence of a known infective dose, scientists either use their limit of detection of the virus, or a metric such as a 99.9% reduction in ability to infect. Because the range of concentrations of virus is so large, biologists usually consider the log reduction (Eqn. (1)) where a 3-log reduction is the same as a 99.9% reduction.

The selection of active ingredient is an important step in preparation of surfaces that provide ongoing inactivation of SARS-CoV-2 [16]. Research to date has been guided by the reservoir of research on antiviral and other antimicrobial materials. In this connection, although the quaternary ammonium polymeric compounds [17,18] and polyamine polymers [19] have previously shown antimicrobial activity, published work does not demonstrate a reduction in infection of SARS-CoV-2 [16,20]. To date, copper, its compounds, and silver have shown promising antiviral activity against SARS-CoV-2 [16,21–23] and were identified as potentially active elements.

The morphology of the surface can potentially play a role in inactivation of SARS-CoV-2 [24]. Surface roughness or porosity can provide a greater surfaces area and affect wettability.

In this review article, we describe the effect of different surfaces and conditions in lowering the infectivity of SARS-CoV-2. First, we review the viability of the virus on common material surfaces, and then the effect of environment conditions on the virus is assessed. A major section is devoted to the introduction of current anti–SARS-CoV-2 surfaces and coatings. Next, the current knowledge in antiviral face masks is reviewed. Finally, other methods of inactivating SARS-CoV-2 on surfaces are discussed. There are two prior reviews of the surface stability of SARS-CoV-2 by Bueckert et al. [25] and Hasan et al. [26].

SARS-CoV-2 RNA on public surfaces

RNA from SARS-CoV-2 has been found on surfaces in hospitals [27–32], laboratories [33], and public places [32,34]. Here we summarize some of the results of sampling for viral RNA by the polymerase chain reaction (PCR) technique. The result of this test does not discriminate virus that is able to infect cells from virus that has been inactivated, but simply gives the total RNA that is present. This compares to $TCID_{50}$ measurements (described above), which assay the ability of a sample to infect primate cells. Thus, the results of this section indicate that a viral component was present, not that it was able to infect humans.

Chia et al. [27] detected the SARS-CoV-2 RNA in hospital rooms where COVID-19 patients were kept (average temperature = 23 °C, relative humidity = 53–59%). Hospital surfaces were tested for SARS-CoV-2 RNA using PCR techniques. The researchers tested 245 surfaces in 30 rooms. The most likely places to be contaminated were the floor (65%), followed by the air exhaust vent (60%), bed rail (59%), bedside locker (47%), cardiac table (~40%), electrical switch (~34%), chair (~34%), and toilet seat and flush (~28%). Chia et al. found higher rates of contamination in the first week of illness compared to subsequent weeks [27].

Ong et al. [31] tested high-touch surfaces in the hospital rooms of three COVID-19 patients. The researchers tested 28 surfaces (from 26 solid types) for the SARS-CoV-2 RNA using real-time reverse transcriptase-polymerase chain reaction (RT-PCR). Prior to cleaning, RNA was detected on 61% of the surfaces. Subsequent to cleaning with sodium dichloroisocyanurate, RNA was not detected on any surface. This showed the effectiveness of common disinfection methods. However, it is costly and time-consuming to routinely clean numerous objects. As explained in detail below, an alternative or supplemental process is to use surface coatings that can be applied to continuously inactivate SARS-CoV-2 without expensive and time-consuming cleaning routines.

Harvey et al. [34] explored the presence of virus in public places over 2 months (from April to June 2020). They checked door handles, gas pump handles, ATM keypads, garbage cans, crosswalk buttons in essential businesses (i.e. grocery stores, banks, gas stations, restaurants, laundromats, and a few more). Surfaces were sampled using flocked polypropylene swabs to detect SARS-CoV-2 RNA with quantitative RT-PCR (RT-qPCR). They found that 8.3% of 348 tested objects had positive results, which is a large percentage for objects accessible to the public. The most contaminated surfaces were a trash can handle and a liquor store door handle. The percent of contaminated surfaces

decreased when temperature increased (it has been shown that SARS-CoV-2 virus half-life shortens with increasing temperature [35,36]).

Fernández-de-Mera et al. [32] also reported the detection of viral RNA on high-touch items in public spaces. They investigated 14 surfaces in public sites, including pharmacies, post offices, supermarkets, a police station, a city hall, and a few more. The researchers [32] used Dry-Sponges (pre-hydrated with an isotonic surfactant and a virus-inactivating liquid) and RT-PCR to detect SARS-CoV-2 virus RNA. They reported that 21.4% (3 out of 14) of the tested surfaces had positive results.

In summary, the studies showed that there is evidence of widespread distribution of SARS-CoV-2 (where active or not) on public surfaces during the pandemic.

Pioneering studies of the longevity of SARS-CoV-2 on solids

Two early and seminal papers by van Doremalen et al. [8] and by Chin et al. [9] started our understanding of the stability on solids. Each of these papers showed that the infective titer depended on the material type and that the titer decayed approximately exponentially with time. Van Doremalen et al. [8] examined the stability on copper, cardboard, stainless steel, and plastic. From our perspective, the most important findings were that (a) the half-life of SARS-CoV-2 was strongly dependent on the material, 1 h for copper and 7 h on plastic, which was our basis for thinking that a material or coating could be developed to minimize the longevity of the virus and (b) that the half-life was shortest on copper, which provided a starting point for choosing an active material. From the public perspective, the idea that the virus could last for days on surfaces led to increased fear of contracting COVID-19 from surfaces and led to widespread decontamination of surfaces.

At about the same time Chin et al. [9], examined the stability of SARS-CoV-2 on paper, tissue paper, wood, cloth, glass, a Hong Kong banknote, stainless steel, plastic, and the inner and outer layer of a facemask (as well as several disinfectants). They also found a strong dependence of the viral titer on the material type. In particular, they found that the titer was low on fibrous materials, which we shall discuss later. One particularly interesting result, which has not been widely discussed, is that the stability in suspension at 60 min was independent of the suspension pH in the range 3−10, a range which spans the protonation of isolated carboxylates and the deprotonation of amines. The infectivity of the virus is not sensitive to temporary changes in the charged state of the proteins on the exterior, showing a strong resilience to denaturation.

Chin et al. [9] also showed that the virus was less stable at greater temperature, with the viral titer barely decaying over 14 days at 4 °C and yet becoming undetectable within 5 min at 70 °C. Clearly temperature has a much stronger influence than pH. The dependence on temperature not only points to a means of disinfection, but also signals the need to consider environmental conditions when comparing results on different solids.

The early studies focused on viral stability on everyday objects, presumably with a view to providing immediate public health information, and not on well-characterized surfaces. Subsequently, there has been a move to study well-characterized solids to elucidate chemistry relationships between activity and chemistry or structure.

Effect of environmental conditions

Later work by Biryukov et al. [35], Matson et al. [37], and Riddell et al. [36] confirmed Chin et al.'s result showing the loss of stability at high temperature. Biryukov et al. and Matson et al. demonstrated that the virus was less stable on solids that were kept at higher humidity. The effect of humidity is a curious result. Higher humidity should hasten evaporation of the droplet and therefore hasten the large change in viral environment that occurs when the virus is dehydrated. We would have expected a higher humidity to preserve the virus; however, this is clearly not observed.

Matson et al. [37] showed that other chemical components in the droplet affected the longevity. The virus was more stable in nasal mucous than in sputum at 21 °C and 27 °C. Pastorino et al. [38] evaluated the stability of the virus on addition of 10 g/L bovine serum albumin (BSA). They added BSA to change the culture medium in order to mimic the protein present in the human mucus and other respiratory fluids. Although the virus was inactivated on glass and aluminum after 44 h and 4 h, respectively, its stability was prolonged when moderate BSA concentration was added to the medium, to the point that the virus remained viable on all the surfaces even after 100 h [38]. The medium was not found to be important [37] in an unpublished study by Szpiro et al. (Szpiro et al., medRxiv doi: 10.1101/2020.08.22.20180042).

Stability on common solids

In this section, we focus on the stability of SARS-CoV-2 on common solids. Riddell et al. [36] investigated brushed stainless steel, an Australian polymer banknote, paper banknotes, glass, vinyl, and cotton cloth in the dark to eliminate the potential effect of UV inactivation. Their experiments showed that although infectivity from cotton was poor, the virus remained detectable for 28 days on other surfaces at 20 °C. Conversely, this duration declined to 1 day at 40 °C. Another study [39]