Effect of Surface Porosity on SARS-CoV-2 Fomite Infectivity

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Cite This: ACS Omega 2022, 7, 18238–18246

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ABSTRACT: Previous reports indicated the low stability of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) on various porous surfaces, but the role of porosity was unclear because there was no direct comparison between porous and nonporous solids of the same chemistry. Through comparing pairs of solids with very similar chemistry, we find that porosity is important: porous glass has a much lower infectivity than nonporous glass. However, porosity is not sufficient to lower infectivity; permeability, which is the ability of a liquid to move through a material, is the important parameter. We show this by comparing a pair of porous CuO coatings where the pores are accessible in one case and inaccessible in the other case. When the pores are inaccessible, the infectivity remains similar to that for nonporous solids. Thus, for both glass and CuO, it is the access to porosity that decreases the infectivity of extracted liquid droplets. Having established the importance of permeability, there is the open question of the mechanism of changing the infectivity of SARS-CoV-2. Several hypotheses are possible, such as increasing the difficulty of extracting the virus from the solid, changing the drying time, increasing the surface area of active ingredient, etc. Reverse transcriptase quantitative polymerase chain reaction (RT-qPCR) measurements show that less viral DNA is extracted from a permeable surface, suggesting that the virus becomes trapped in the pores. Finally, we consider the effect of drying. We show that permeability and the water contact angle on the solid have effects on the drying time of a contaminated droplet, which may in turn affect infectivity.

INTRODUCTION

Coronavirus infectious disease 2019 (COVID-19) has been responsible for about 220 million cases and 5.1 million deaths worldwide (as of November 2021)¹ and has dramatically altered the world economy. Despite the temporary roll-back in vaccines in early 2021, the emergence of variants, such as the delta and omicron variants, has caused new surges in the number of new cases caused by the administration of other viruses.¹² SARS-CoV-2 can remain viable and infectious on surfaces for up to one week¹³,¹⁴ so the period of vulnerability to transfer is potentially quite long. Some have challenged the importance of fomite transmission based on the high input titers that were used in experiments,¹⁵ but the titers (10⁵–10⁶ TCID₅₀/mL¹⁴ and 10⁷.⁸ TCID₅₀/mL¹³) were in the range of the amount of SARS-CoV-2 found in the nose or throat of patients.¹⁶ A recent review on this topic concludes that more research is required to determine the risk.¹⁷ The infectious dose in humans is, at present, unknown, but in a transmission could occur when speaking, coughing, or sneezing by an infected person generates contaminated droplets that are large enough to land on objects. If a healthy person touches the contaminated object and then touches their nose or mouth, the virus could transfer. Surface sampling during the COVID-19 pandemic revealed a high percentage of surfaces that contained SARS-CoV-2 RNA both in hospital settings⁵,⁶ and on common touch surfaces (3–25%).¹⁰ Recent work shows that SARS-CoV-2 can be transferred from fomites to a finger,¹¹ as can other viruses.¹² SARS-CoV-2 can remain viable and infectious on surfaces for up to one week¹³,¹⁴ so the period of vulnerability to transfer is potentially quite long. Some have challenged the importance of fomite transmission based on the high input titers that were used in experiments,¹⁵ but the titers (10⁵–10⁶ TCID₅₀/mL¹⁴ and 10⁷.⁸ TCID₅₀/mL¹³) were in the range of the amount of SARS-CoV-2 found in the nose or throat of patients.¹⁶ A recent review on this topic concludes that more research is required to determine the risk.¹⁷ The infectious dose in humans is, at present, unknown, but in a

Received: December 5, 2021
Accepted: March 18, 2022
Published: May 23, 2022
porous fomites.13,26,37 For example, Riddell et al.37 noted the infectivity of SARS-CoV-2 through fomites. Various studies protective equipment that is constructed from important for both common-touch surfaces and for personal protective equipment that is constructed from fibers, such as facemasks and clothing.38

The observed dependence of the stability of SARS-CoV-2 on different materials13,14 suggests that materials can be specifically developed to reduce the lifetime of SARS-CoV-2 on solids. Coatings are particularly attractive because they can be applied to a variety of different objects with a low amount of active material,22 and this idea has stimulated the fabrication of antiviral coatings.22−32 To date, surface coatings of copper23,24 and its two oxide forms,22,25−27 silver oxide,31 zinc oxide,32 and light-activated titanium dioxide29 have shown promising results for practical application on common touch surfaces with a high frequency of contacts. Moreover, silver25,33 and zinc species34,35 have also accelerated the inactivation of this virus. Hasan et al.36 showed that SARS-CoV-2 has a reduced lifetime on nanostructured aluminum surfaces and hypothesized that the effect may be due to the trapping of the virus. This suggests that the surface structure and chemistry may be important.

In this work, we focus on the effect of porosity on the infectivity of SARS-CoV-2 through fomites. Various studies have shown the low infectivity of liquid that is recovered from porous fomites.13,26,37 For example, Riddell et al.37 noted the poor infectivity from cotton, and Hosseini et al.26 noted the poor infectivity from porous CuO. However, a comparison between cotton and glass or porous CuO and glass does not directly determine the effect of porosity. Porosity may be important for both common-touch surfaces and for personal protective equipment that is constructed from fibers, such as facemasks and clothing.38−40

It is important here to distinguish the difference between porosity and permeability. Porosity, meaning the presence of pores, is irrelevant to the present discussion if the pores are not connected to the surface where the viral suspension lands. Permeability refers to the ability of liquid to travel through the porous structure. If pores with an appropriate wettability are connected to the surface, then a droplet on the surface can be drawn into the solid, i.e., imbibe,41 rather than remain on top of the solid surface. We hypothesize that imbibition is a critical characteristic that determines the infectivity of porous surfaces.

Here we compare the effect of porosity on SARS-CoV-2 surface infectivity for pairs of surfaces of very similar materials. First, we examine glass, which is an inactive material;13,22 we compare porous and permeable glass to nonporous glass. Then, we compare two porous materials made from CuO, where the porosity is accessible in one case due to wettability by water and inaccessible in the second case due to the nonwettability of the pores. In the second case, the coating is impermeable and imbibition does not occur. Therefore, although porosity is present, the pores are inaccessible, so we hypothesize that the porosity is irrelevant to reducing the infectivity of SARS-CoV-2. The nonwettability was introduced through the addition of hydrophobic polyurethane. CuO has previously been described as an anti-SARS-CoV-2 agent,25,26 whereas polyurethane has been found to be inactive against SARS-CoV-2.25 Finally, we discuss the mechanisms of the reduced infectivity of the porous surfaces.

### MATERIALS AND METHODS

**Materials.** 100% ACS-grade ethanol, 70% nitric acid, 70% reagent-grade ethanol, and glass slides (model number 48300-026) were purchased from VWR. Smooth crushed glass (270−1000 grit, catalog number 64223704) was obtained from MSC Industrial Supply Company. Polyurethane (Minwax, fast drying) was purchased from Lowe’s Home Improvement Store. CuO particles (model number HP III, 5.4 μm) and CuO particles (model number 13600FM, 2.8 μm) were donated by American Chemet Corporation. Water for all sample preparation was purified by a Milli-Q Reference system.

**Preparation of Non-Porous Glass (NP-Glass).** The cleaning of the glass pieces has been previously reported.22 Briefly, glass slides were cut into 1.2 × 1.2 cm pieces and rinsed three times in water. Next, the glass pieces were soaked in 70% ethanol for 15 min, rinsed three times with water, and soaked in 6 M nitric acid for 20 min. Finally, samples were rinsed several times with water to ensure that the acid was completely removed from the surface and then dried with a nitrogen gas stream.

**Fabrication of Porous Glass Coatings (P-Glass).** Glass slides were cut into 15 × 15 mm pieces, rinsed with water, and dried using a nitrogen gas stream. The crushed glass was milled for 95 h in a generic mill jar (U.S. Stoneware roller mill) with alumina milling media with the rate of 0.5 rotations per second to obtain small glass particles. After a suspension of 10.5 wt % milled glass in ethanol was sonicated for 6 min, 280 μL of the suspension was applied on each of the 1.5 × 1.5 cm glass pieces. Upon the evaporation of ethanol at room temperature, the samples were heat-treated at 120 °C for 10 min, then the temperature was increased gradually to 617 °C over a period of 30 min. The temperature was held at 617 °C for 2 h to enable early-stage sintering. Next, the furnace was switched off, and the samples were cooled overnight. Lastly, samples were cleaned using the same procedure used for the NP-Glass surfaces and dried using a nitrogen gas stream.

**Fabrication of Porous but Non-Permeable Cupric Oxide Coatings (NP-CuO).** To obtain a cupric oxide surface that does not imbibe water, we fabricated a coating that was hydrophobic enough to prevent infiltration of the droplet into the pores (no imbibition). First, a thin film of polyurethane was applied on a glass slide for 8 min. Next, a suspension of 10 wt % cupric oxide in ethanol was sonicated for 3 min, and 1 mL of this suspension was applied on top of the thin polyurethane film. The film was left at room temperature to dry. The sample was heat-treated at 120 °C for 2 h to cure the polyurethane and get a robust coating. Finally, the sample was cut into 1.2 × 1.2 cm pieces, rinsed with DI water, and blown using a nitrogen stream to remove the free particles.

**Fabrication of Porous and Permeable Cupric Oxide Coatings (P-CuO).** We have previously reported the fabrication procedure of a porous cupric oxide coating.26 Briefly, a solution of 16 wt % cupric oxide in ethanol was sonicated for 6 min, and 200 μL of this suspension was applied on a 1.5 × 1.5 cm glass piece. The glass piece was left at room temperature to dry. Next, samples were heat-treated at 120 °C, and the temperature was gradually increased to 700 °C over a period of 40 min to fully oxidize Cu2O to CuO and generate early-stage necks between the particles. After 2 h, the furnace was switched off, and the samples were cooled overnight.
Finally, samples were rinsed with water and dried using a nitrogen gas stream to remove the loose particles.

**TMCS deposition.** We deposited trimethylchlorosilane (TMCS) onto glass to study the dependence of the drying time on the contact angle of a water droplet. We employed a vapor deposition method where NP-Glass was initially plasma treated with O2 at P < 200 mTorr and 100 W and then exposed to the vapors of TMCS in a sealed glass container. After 24 h, samples where sonicated in ethanol for 1 min to remove any unattached molecules on the surface. Finally, samples were dried using a nitrogen stream. The results of the contact angle measurements confirmed the deposition of TMCS on the surface, where the advancing, sessile, and receding contact angles were measured on average to be 97 ± 4°, 89 ± 2°, and 74 ± 2° respectively. Errors indicate the 95% confidence intervals.

**Characterization of the Samples.** The crystalline structures of CuO samples were studied using X-ray diffraction (XRD, Bruker D8 Advance diffractometer, monochromatic copper Kα X-ray source, λ = 1.5418 Å). The chemical composition of the outermost few nanometers of the surface of the glass samples was measured using X-ray photoelectron spectroscopy (XPS, PHI VersaProbe III, monochromatic Al Kα source of 1486.6 eV). Scanning electron microscopy (SEM, JEOL JSM-IT500) was used to take images to study the topography of the surfaces of the samples. Contact angle measurements and droplet drying images utilized a First Ten Angstroms FTA125 apparatus.

**SARS-CoV-2 Titrations.** We used the 50% tissue culture infective dose (TCID50) method to measure the viable virus titer of SARS-CoV-2 (BetaCoV/Hong Kong/VM20001061/2020) on the surface. The TCID50 assay has been widely accepted as a viral titration method for viruses, including SARS-CoV-2. These cells were cultured in Dulbecco’s modified Eagle medium supplemented with 2% fetal bovine serum and 1% v/v penicillin-streptomycin at 37 °C and 5% CO2. All samples were initially decontaminated by rinsing them with 70% ethanol and drying them at 37 °C. Environmental conditions were set to 22–23 °C and 60–70% humidity, and a 5 μL droplet containing 7.3 log(TCID50/mL) SARS-CoV-2 was applied on each solid. After a predefined period of time, the viable virus on the surface was eluted by soaking the sample in balanced salt solution (pH = 7.4) supplemented with 0.5% (w/v) glucose, for >30 min. Next, serial dilutions of the eluent were used to infect Vero E6 cells and incubated the samples for five days. No cytopathic effect was observed. Previously, we reported that DMEM that was placed in contact with CuO for 24 h, mixed with the virus, and then exposed to Vero E6 cells also had no effect on Vero E6 cells.26

**Reverse Transcriptase Quantitative Polymerase Chain Reaction (RT-qPCR).** Viral RNA was extracted from the eluted virus with the QiAamp viral RNA kit (Qiagen). Quantitative RT-qPCR on the N gene of the SARS-CoV-2 was performed as described by Chu et al.44

**Statistics.** All experiments were performed with three independent sample replicates. Error bars denote the standard deviation from the mean values. For TCID50 measurements, we find that residuals from mean are distributed normally after a log transformation, so the indicated means are the means of log(TCID50/mL) measurements. Hypothesis testing was done with Student’s t tests, where p-values less than 0.05 were indicative of significant results. Note that some of the results are below the limit of detection. In statistical tests, these were calculated at the detection limit, which overestimates the mean and underestimates the standard deviation.

**RESULTS**

**Characterization of Surfaces.** Our hypothesis is that imbibition affects the infectivity of surfaces contaminated by SARS-CoV-2 droplets, so we first examined the imbibition of our test surfaces. A 5 μL water droplet spreads on NP-Glass to give a static contact angle of 24.5° ± 0.3°, whereas the drop is imbibed into P-Glass within seconds and spreads radially within the coating. On NP-CuO, the droplet is not imbibed and has a contact angle of 109° ± 5° (Figure S2). On P-CuO the droplet is rapidly and spontaneously imbibed into the pores (Figure S3). Pores in NP-CuO are inaccessible due to the high contact angle caused by the presence of polyurethane as an inactive, adhesive agent. We estimated the porosity of the porous samples by measuring the mass of water that was imbibed by the test solids (see the Supporting Information for the details). The measured porosity was 33 ± 2% for P-CuO and 43 ± 5% for P-Glass. Errors indicate the standard deviation of three independent measurements.

To isolate the effect of imbibition from surface chemistry, it is necessary to compare very similar porous and nonporous materials in virus viability tests. Since CuO is crystalline, we used XRD to compare the crystal structures of the NP-CuO and P-CuO samples. Figure 1 shows that these samples have the same XRD pattern, which matches the monoclinic XRD

**Cytotoxicity.** To check for potential toxicity of materials that leached from the coatings to Vero E6 cells, we repeated the assay without the virus. That is, we immersed each sample in the viral transport medium for 30 min, then applied the liquid Vero E6 cells and incubated the samples for five days. No cytopathic effect was observed. Previously, we reported that DMEM that was placed in contact with CuO for 24 h,

![Figure 1. X-ray diffraction patterns of NP-CuO and P-CuO, which confirm that both coatings contained cupric oxide. The numbers shown above the peaks are the Miller indices.](https://doi.org/10.1021/acsomega.1c06880)
pattern for CuO previously reported in the literature.\textsuperscript{55–57} Therefore, the crystalline portion of the two coatings is the same material.

We used XPS to compare the surface composition of NP-Glass and P-Glass. Table 1 shows that the two glass samples have very similar elemental compositions and are both soda lime glass. SEM images were used to reveal the topography of the samples. Figure 2 shows the surface of each sample and confirms the porosity of P-Glass, P-CuO, and NP-CuO as well as the nonporous nature of NP-Glass. In summary, we have fabricated two pairs of materials where the chemistry is very similar but the permeability is very different.

Porosity Accelerates the Decay of the Infectivity of SARS-CoV-2 on Solids. We measured the infectivity of SARS-CoV-2 via the TCID\textsubscript{50} assay on the pairs of samples. Figure 3A shows the decay of the SARS-CoV-2 virus titer on NP-Glass and P-Glass samples over the course of time. The zero time point represents a sample where SARS-CoV-2 was extracted within 1 min of the infected droplet being placed on the surface. The average virus titer measured on NP-Glass decayed insignificantly over time (\( p = 0.39 \)). This result is in agreement with the inactive nature of glass,\textsuperscript{13} where the virus titer does not significantly decrease over the course of time. In contrast, on P-Glass the average virus titer dropped by 1.9 logs (79\times) at 0 min. This drop shows that most of the virus was not recovered after the droplet was imbibed by P-Glass.

To investigate which factors are important in SARS-CoV-2 infectivity, we performed a regression analysis with time, permeability, and their interaction using the following equation:

\[
\log[\text{TCID}_{50}/\text{mL}] = A - Bt - Cp - Dt \cdot p
\]  

Figure 3. Decay of SARS-CoV-2 virus titer on (A) impermeable NP-Glass and permeable P-Glass and (B) impermeable NP-CuO and permeable P-CuO. Circles show the individual data points, \( \times \) indicates the average titer value, and shaded regions indicate the standard deviation. The detection limit of 90 TCID\textsubscript{50}/mL is illustrated by a dashed line. The comparisons between the permeable and impermeable coatings show that the virus titer is much lower on permeable surfaces.

Table 1. Comparison between the Elemental Ratios of the NP-Glass and P-Glass Surfaces as Measured by XPS\textsuperscript{a}

<table>
<thead>
<tr>
<th>element</th>
<th>NP-Glass atomic %</th>
<th>P-Glass atomic %</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>58.2</td>
<td>60.9</td>
</tr>
<tr>
<td>Si</td>
<td>21.1</td>
<td>22.7</td>
</tr>
<tr>
<td>C</td>
<td>13.9</td>
<td>12</td>
</tr>
<tr>
<td>Na</td>
<td>3.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Ca</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Mg</td>
<td>1.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Zn</td>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>N</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Cl</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Al</td>
<td>0</td>
<td>0.4</td>
</tr>
</tbody>
</table>

\textsuperscript{a}The elemental compositions are very similar, and both materials are soda lime glass. Reprinted with permission from ref 32. Copyright 2021, American Chemical Society.

Figure 2. SEM images of (A) NP-Glass, (B) P-Glass, (C) NP-CuO, and (D) P-CuO. Images clearly show the porous nature of P-Glass and P-CuO and the nonporous nature of NP-Glass. Although pores are observable on the surface of NP-CuO, a water droplet sits on the surface (see Figure S2 in the Supporting Information) to generate a contact angle of 109° ± 5°.
where \( t \) is the time in minutes and \( p \) indicates the permeability (0 = impermeable and 1 = permeable). The results showed that permeability is the only significant contributor to the difference between virus titer results on NP-Glass and P-Glass (see values of \( p \) in Table 2). SARS-CoV-2 is a virus, not a living cell, and although it slowly inactivates on its own on a glass surface over a longer time period, the contribution of time is significantly less than that of permeability. The interaction between permeability and time was not resolved here.

From a practical perspective, the infectivity of the virus recovered from the porous glass was reduced by 99.8% after 15 min and by >99.9% after 30 min, which should translate into a much lower chance of infection from porous glass compared to nonporous glass.

Results for CuO in Figure 2B again show a large reduction of infectivity on the coating where the droplet was imbibed compared to the impermeable sample. At zero time, the permeable CuO has a 2 log reduction compared to the impermeable CuO, which is similar to the effect on glass. The virus titer measured after 15 and 30 min fell below the detection limit. The comparison between the virus titer in the input and that in P-CuO shows that at least 99.96% of the infectivity was lost on P-CuO after 15 min (\( p = 10^{-33} \)).

The regression analysis performed using eq 1 again shows that permeability is the only significant factor for the infectivity of CuO in this model (See Table 2). The mild activity of CuO against SARS-CoV-2 that was observed in previously literature would appear as the significance of the \( t \)-\( p \) cross-term, but it was difficult to resolve ongoing decreases when the titer was only 1.5 logs above the detection limit at time zero.

**DISCUSSION**

**Effect of Imbibition on Infectivity and Recovery.** The results show that the SARS-CoV-2 virus titer on surfaces that imbibe contaminated droplets is significantly lower than that on nonporous surfaces. The results for CuO show that the porosity itself is not sufficient for the surface to decrease infectivity; the permeability to water that leads to imbibition correlates with the loss of infectivity.

To be effective at combating potential infection, imbibition must occur quickly, that is, more quickly than the time between contamination and a person touching the solid. The imbibition time into a single straight cylindrical pore can be estimated by the Lucas–Washburn equation, where the speed of imbibition depends on the dynamic viscosity, the solid–liquid interfacial tension, the radius of the pore, and the contact angle of the liquid on the solid. Cai and Yu modified the Washburn equation to include the effect of the tortuosity of the pores. The calculation shows that the imbibition of a 5 \( \mu \)L water droplet by a tortuous porous surface with a pore diameter of 1 \( \mu \)m takes only seconds (see the Supporting Information), consistent with our results. Thus, imbibition is an effective way of quickly reducing surface infectivity. The time of imbibition is much smaller than the duration of the stability of SARS-CoV-2. Hence, it is reasonable to assume that the virus titer from the droplets is reduced within seconds on macroporous materials because of imbibition. The viscosity of saliva is about 70 times that of water, but because of the square root dependence of viscosity in the Washburn equation, imbibition should still occur within about 1 min. Some respiratory fluids are very viscous and may not imbibe faster than the time between consecutive touches.

Imbibition brings about two decisive effects that lead to the reduction of the virus titer on porous surfaces. First, the virions suspended in a contaminated droplet are carried into the pores as the droplet is imbibed by the porous medium. Surfaces forces may trap virions within the pores, or the narrow channels may simply limit the transport of the virus. Note that the transport of the virus into the pores is hastened by the initial flow of water into the pores as the liquid wets the pore walls, whereas the transport of the virus out of the pores into water occurs without the aid of a flux of a carrier fluid. The second effect of imbibition is the change in the drying time of the droplet. The effect of drying will be discussed in the following sections.

On P-Glass, we hypothesize that the loss of infectivity is caused by virus trapping rather than inactivation of the virion because the glass is inactive. The TCID\(_{50}\) assay measures infection, so it does not discriminate between virus inactivation and trapping. We therefore tested the trapping hypothesis with RT-qPCR measurements. RT-qPCR measures the number of viral genes present (copy number) independent of whether the virus is viable. Therefore, it measures our extraction efficiency more directly. One potential confounding factor to consider is that the glass walls of the porous material might damage the viral RNA such that the gene is not measured by RT-qPCR. We consider this unlikely because, despite the widespread use of glassware in science, we find no record of this effect.

Our results show that the SARS-CoV-2 N gene copy number is 2 logs smaller (\( p = 2 \times 10^{-7} \)) on P-Glass than that on NP-Glass after 30 min (the data are shown in Table S1). We also found that the virus N gene copy number on P-CuO drops by 1.5 logs (\( p = 2 \times 10^{-5} \)) after 30 min.

TCID\(_{50}\) measures infectivity, whereas RT-qPCR measures gene number. The fact that they each fall by about 2 logs immediately after imbibition suggests that the virus is merely trapped or absorbed in the pores. This trapping is consequential. In the absence of cells, the virus does not have metabolism, so it becomes inactivated over time even without contacting a specific active material. Therefore, if SARS-CoV-2 remains trapped for long enough, the titer will decay and presumably be less able to infect people.

**Is CuO an Active Material?** Prior work suggested that the CuO coating was active, but until now the question remained open. Because the viral titer is so low on porous CuO due to imbibition and trapping, it is difficult to resolve the activity of CuO. Now, however, we have an opportunity for better resolution through the use of the nonimbibing CuO sample. Figure 4 compares the TCID\(_{50}\) assay values on glass and CuO, each with no imbibition. The virus titer is about 1 log lower for CuO at 1 h (\( p = 8 \times 10^{-5} \)) and at least 1.5 logs lower at 24 h (\( p = 5 \times 10^{-3} \)). This greater reduction indicates an active

Table 2. Linear Regression Coefficients for Equation 1

<table>
<thead>
<tr>
<th>parameter</th>
<th>coefficient</th>
<th>glass ( p )</th>
<th>value</th>
<th>cupric oxide ( p )</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>A</td>
<td>5.76</td>
<td>2.9 ( \times ) ( 10^{-10} )</td>
<td>5.36</td>
<td>2.4 ( \times ) ( 10^{-10} )</td>
</tr>
<tr>
<td>( p )</td>
<td>B</td>
<td>2.13</td>
<td>1.1 ( \times ) ( 10^{-5} )</td>
<td>2.22</td>
<td>3.8 ( \times ) ( 10^{-4} )</td>
</tr>
<tr>
<td>( t )</td>
<td>C</td>
<td>0.012</td>
<td>0.54</td>
<td>0.012</td>
<td>0.49</td>
</tr>
<tr>
<td>( t \cdot p )</td>
<td>D</td>
<td>0.043</td>
<td>0.13</td>
<td>0.035</td>
<td>0.18</td>
</tr>
</tbody>
</table>

*The linear regression was run with time, \( t \), in units of minutes and porosity, \( p \), as a categorical factor (0 = impermeable and 1 = permeable). Permeability is also significant when we run a model without \( t \) or \( t \cdot p \).*
material. Thus, for porous CuO, there are two mechanisms for the loss of infectivity: the immediate drop after imbibition due to poor recovery from the pores and the slow loss due to the presence of the active material. If the virus suspension is imbibed by the pores, there will be a greater surface area of active ingredient and faster diffusion, which we expect will make an active permeable material much more effective than an active impermeable material.

**Effect of Drying.** In general, the improvement in the antiviral activity of porous surfaces has been attributed to (1) a reduced drying time, (2) the virus being trapped and absorbed within the pores, (3) the presence of a huge active surface area where diffusion distances for virions to reach to the active surface and be inactivated are smaller, and (4) protection from normal wear and tear (abrasion).28

We now turn our attention to the second effect of imbibition on the reduction of SARS-CoV-2 titer on surfaces, namely drying. Drying has been reported to play an important role in the inactivation of coronaviruses and other viruses.62,63 Chatterjee et al.52 found a direct relationship between the duration of the drying time of a droplet and the stability of SARS-CoV-2 on surfaces.

The time courses of the drying of a water droplet on porous and nonporous coatings at 25 °C and 30% humidity are shown in Figure 5. Comparing two materials of the same chemistry, namely glass, the droplet evaporated in about 6 min on porous glass and in about 23 min on nonporous glass. The same trend occurs for other materials. Drying occurred in about 6 min for P-CuO and in about 35 min for NP-CuO, where the water droplet was unable to enter the pores because of hydrophobicity. Clearly, imbibition leads to much faster drying (p < 10−15).

The drying is faster on the nonporous glass than on the impermeable CuO. We hypothesized that this was due to the difference in the area of the air–water interface, which is where evaporation must occur. NP-CuO has a higher contact angle (109 ± 5°) than the NP glass (24.5 ± 0.3°), which will expose less surface area. To test for this effect, we made the glass hydrophobic by a reaction with TMCS to give an advancing contact angle of 97° ± 4° and a receding angle of 74° ± 2°. After hydrophobization, the drying time increased from about 22 to 32 min and became similar to the drying time for the hydrophobic CuO particle surface.

Once we correct for contact angle, the drying times fall into two separate categories: fast for the permeable surfaces and slow for the impermeable surfaces. We again expect this to be due to the increase in the air–liquid surface area.

Even for an inactive material, drying may be important for inactivating viruses because of the loss of necessary water or the increased concentration of solutes such as salt from the original droplet. For an active surface that leaches ions, drying may also concentrate ions that are designed to be toxic to the virus such as copper,22 silver,25 and zinc,35 ions that are known to be toxic to SARS-CoV-2.

## CONCLUSION

We evaluated the effect of porosity on the SARS-CoV-2 titer (infectivity) of liquid extracted from deliberately contaminated solid surfaces. Imbibition of the droplet into the porous coating caused a large drop in infectivity, regardless of whether the material had an active ingredient. Based on RT-qPCR measurements, we attribute this effect to the virus being trapped in the pores. A simple porous coating was found to be highly effective, suggesting a new method to enormously increase the efficacy of anti-SARS-CoV-2 coatings. We would expect that this physical effect would also apply to other viruses. We consider a porous active material to be an ideal coating material for reducing the potential infectivity of surfaces because the infectivity is decreased by both trapping and by the active ingredient. Finally, we showed that permeable coatings dry more rapidly than impermeable coatings, an effect that may also contribute to hastening the inactivation of SARS-CoV-2.
Control for the effect of extracting an active ingredient into the eluent medium, time lapses of a droplet drying on NP-CuO and a droplet being imbibed by P-CuO, RT-qPCR measurements, raw data of the SARS-CoV-2 virus titer, and demonstration of porosity elimination for porous samples (PDF).

AUTHOR INFORMATION

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Notes

The authors declare the following competing financial interest(s): W.D. declares part ownership in a startup company that intends to produce surface coatings. Other authors declare no conflict of interest.

ACKNOWLEDGMENTS

The authors acknowledge use of electron microscopy and X-ray diffraction facilities within the Nanoscale Characterization and Fabrication Laboratory and Material Characterization Laboratory at Virginia Polytechnic Institute. The authors also thank Thomas Staley for milling the glass particle to the appropriate size. We also thank Xu Feng for capturing the XPS spectra and acknowledge the use of the Surface Analysis Laboratory in the Department of Chemistry at Virginia Tech, which is supported by the National Science Foundation under Grant CHE-1531834. This work was supported by the National Science Foundation under Grant CBET-1902364, the Health and Medical Research Fund (COVID190116), and the National Institute of Allergy and Infectious Diseases (contract HHSN272201400006C).

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