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SARS-CoV-2 Viability on 16 Common Indoor Surface Finish Materials

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Abstract

Aim: This study investigated the stability of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) on 16 common environmental surface materials. **Background:** SARS-CoV-2 is the causative agent of severe coronavirus disease, a significant public health concern that quickly led to a pandemic. Contamination of environmental surface materials is of concern, with previous studies identifying long-term detection of infectious particles on surfaces. These contaminated surfaces create an increased risk for contact transmission. **Methods:** Surface materials were inoculated with 10,000 plaque forming units and samples were collected 4, 8, 12, 24, 30, 48, and 168 hours post infection (hpi). Viral titers were determined for each sample and time point using plaque assays. Nonparametric modeling utilized the Turnbull algorithm for interval-censored data. Maximum likelihood estimates for the survival curve were calculated. Parametric proportional hazards regression models for interval censored data were used to explore survival time across the surface materials. **Results:** There was a sharp decline in recoverable virus after 4 hpi for all tested surfaces. By 12 hpi, infectious SARS-CoV-2 was recoverable from only four surfaces; and by 30 hr, the virus was recoverable from only one surface. There were differences in survival curves based on the materials although some groups of materials are similar, both statistically and practically. **Conclusions:** While very low amounts of infectious SARS-CoV-2 are recoverable over time, there remains a risk of viral transmission by surface contamination in indoor environments. Individuals and institutions must follow appropriate procedures to decontaminate indoor environment and increase diligence for hand hygiene and personal protective equipment.

Keywords

coronavirus, SARS-CoV-2, COVID-19, viral kinetics, surface, fomite, finish materials, environmental design, environmental surface materials

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Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), a beta-coronavirus, is the causative agent of severe coronavirus disease (COVID-19). This disease, declared a pandemic by the World Health Organization (WHO) in March 2020, continues to cause significant burden. As of November 1, 2020, 46.6 million individuals have been infected internationally, with 9.1 million of those cases within the United States (Center for disease Control and Prevention [CDC], 2020b). COVID-19 is characterized by unresolved systemic hyperinflammation associated with a life threatening "cytokine storm syndrome," leading to multi-organ failure dysfunction in some patients (Mehta et al., 2020; Y. Wu et al., 2020). As research continues to characterize the risk factors for severe disease, and vaccines and therapeutics undergo clinical trials, we still lack an understanding of basic viral kinetics in household, community, and hospital settings. As case counts continue to grow, understanding this information remains critical.

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The role of environmental surface materials contaminated with SARS-CoV-2 for disease transmission remains unclear. Environmental surface materials can be heavily contaminated with SARS-CoV-2 in hospital patient rooms (Cheng et al., 2020; Chia et al., 2020; Santarpia et al., 2020; van Doremalen et al., 2020; S. Wu et al., 2020). Surface contamination may lead to contact transmission, contributing to the spread of COVID-19 (Carraturo et al., 2020; Di Maria et al., 2020; WHO, 2020).

In controlled experiments, human coronaviruses remained infectious on surfaces at room temperature for up to 9 days; recent studies described that SARS-CoV-2 remains on surfaces from a few hours to 6 days (Kampf et al., 2020; van Doremalen et al., 2020). Environmental conditions, specifically higher temperatures and relative humidity, increase the rate of decay of SARS-CoV-2 affecting transmission capability (Biryukov et al., 2020). Chin et al. (2020) and van Doremalen et al. (2020) described differences in stability of the virus across a selection of materials with respect to environmental conditions and material composition, suggesting that environmental factors may influence transmission of the virus in the indoor environment.

Other previous work related to SARS-CoV-2 survival on surfaces has focused on environmental sampling and inoculation studies of indoor surface materials but use reverse transcriptase-polymerase chain reaction and polymerase chain reaction (PCR) as their means of viral detection (Ong et al., 2020; S. Wu et al., 2020; van Doremalen et al., 2020). For example, Guo and colleagues evaluated viral presence via PCR in air and surface samples from hospital surfaces, comparing surfaces in intensive care units (ICUs) and medical surgical units. The authors found that contamination was greater in ICUs (Guo et al., 2020). Of the surfaces tested, 81.3% were positive by PCR. Additionally, SARS-CoV-2 genetic material was widely distributed on floors, with sampling of ICU at 70% positive and medical surgical units at 15.4% (Guo et al., 2020). While this and other studies disclose important information in viral contamination, PCR detects viral nucleic acids and does not directly correlate to the presence of infectious virus (Rubens et al., 2020; Valtierra, 2008). In fact, many studies describe that viral nucleic acids can persist significantly longer that infectious virus in infected individuals and the environment (Biryukov et al., 2020; Chin et al., 2020; Stadnytskyi et al., 2020; Uwamino et al., 2020). The purpose of this study was to investigate the stability of infectious SARS-CoV-2 over a period of 7 days on 16 environmental surface materials commonly used in healthcare, household, and community indoor environments. Here, we report on the stability of SARS-CoV-2 over a period of 168 hr on 16 different surfaces.

Materials and Methods

Test Materials

Sixteen environmental surface materials were included in the study evaluating stability and

Table 1. Environmental Surface Materials Tested for Viability of SARS-CoV-2 Under Laboratory Conditions.

Material	Description
Acrylic solid surface	Solid, nonporous, homogeneous, composed of acrylic resin and natural minerals
Solid surface with CuO	Solid, homogeneous, antimicrobial sheet composed of polyester resins, mineral fillers, and pigments. Cupric oxide is added for antimicrobial properties
Stainless steel, brushed	Chromium–Nickel (CrNi) austenitic alloy sheet with 18% min. chromium and 10% max. nickel, 18 gauge, grade 304
High-pressure laminate	Decorative surface papers impregnated with melamine resins pressed over kraft paper core sheets impregnated with phenolic resin
Copper sheet	Copper Alloy C71000 (Copper Nickel, CuNi) composed of 78%-84% copper and 19.0-23.0% nickel, 18 gauge
Quartz	Primarily a natural material with about 7% polyester resin binder and pigment
Rubber flooring	Vulcanized rubber (natural, synthetic, recycled) commonly with a polyurethane top layer.
Vinyl, sheet, homogeneous	A single layer of PVC with a urethane topcoat
Wood laminate flooring, commercial	Laminated layered flooring system utilizing timber veneer backer board, HDF core, and solid wood wear layer, and may be finished with a urethane coating
Luxury vinyl tile #15	LVT, glue down floor installation, flexible PVC core, stabilization layer
Luxury vinyl tile #21	LVT, floating floor installation, flexible PVC core, stabilization layer, cushion backing, waterproof
Luxury vinyl tile #26	LVT, glue down installation, flexible PVC core, no stabilization layer, no cushion backing
Carpet, commercial	Nylon 6, 20 oz, level loop, polyester backing
Carpet, residential	PET, 25 oz, cut pile, jute backing
Upholstery, nonwoven	Application for seating, 100% polyurethane nonwoven face with polyester backing. Weight 15 oz. Performance for abrasion 100,000 double rubs
Vinyl wall covering, type II	Commercial grade wall covering, 20 oz weight, two layers of solid vinyl applied to a woven or nonwoven fabric substrate. Composition includes plasticizers, stabilizers, and pigments. May contain biocides and flame retardants

degradation of SARS-CoV-2 (Table 1). These test materials were selected based on their substantial and common use in the indoor environment, specifically in healthcare, education, public, and residential environments. A mix of high touch (i.e., stainless steel, solid surface, and high-pressure laminate) and low touch (i.e., rubber flooring, luxury vinyl tile flooring, and vinyl wall covering) surfaces are included in the selected surface materials.

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Sample preparation. Sixteen common indoor surface materials specified for healthcare facilities, community facilities, and residences were procured. Each material was cut to $2'' \times 2''$ samples and prepared by initial cleaning and removal of any adhesives, paper, or other material. Samples were provided to the BSL3 laboratory in triplicate with additional samples of each type for additional testing as needed.

Virus and titration. SARS-CoV-2 (USA-WA1/2020) was obtained from the University of Texas Medical Branch World Reference Center for Emerging Viruses and Arboviruses. The virus was grown on Vero CCL81 (ATCC), aliquoted and titrated by standard plaque assay on Vero E6 cells (Cercopithecus aethiops, Vero 76, clone E6, ATCC CRL-1586) as previously described (Harcourt et al., 2020). Briefly, cells were inoculated with serial dilutions of virus and incubated for 2 days at 37 °C, at which time cells were fixed and plaques were visualized using crystal violet.

The virus stock was sequenced prior to use in the studies to verify sequence agreement with the parent strain.

Virus stability on surfaces. Surface materials ($2'' \times 2''$) were inoculated with 10,000 plaque-forming units (PFU) of SARS-CoV-2 in 50μL and spread evenly across the surface. The surfaces were left to dry at a temperature of 25 °C and 45%–50% relative humidity. At 4, 8, 12, 24, 30, 48, and 168 hours post infection (hpi), samples were washed with 450μL of cell culture media and frozen at −80 °C. Viral titers were determined for each sample and time point by standard plaque assay.

Statistical Analyses

Summary statistics are presented. Each of the 16 materials are categorized based on first reading of zero PFU based on seven time points. Interval censored regression methods were utilized to analyze and model the survival function of the virus on each surface and to compare the functions across surfaces. Each unit of the virus is thought of as an observation in this approach. The event of interest is when the recovery of the virus ends, in other words is no longer present on the surface. The time to the event is interval censored as the precise time the event occurs is not known. Instead, it is only known in which interval of time points PFU cease to be recovered.

The survival function is defined as: $S(t) = P(T > t)$, for $t > 0$, where T is the time in hours that a PFU remains on the surface. Thus, the survival function models the probability that a PFU remains for more than t hours. Nonparametric methods were used to explore the data and both semi-parametric and parametric regression methods to produce models of the survival function.

Nonparametric models. The Turnbull algorithm (Turnbull, 1976), an analog to approaches such as Kaplan–Meier, was used as a nonparametric estimator of the survival function while accounting for interval-censored data (Rodrigues et al., 2018). The estimation method of Anderson-Bergman (2017), implemented in the *icenReg* package in R (R Core Team, 2017), produces maximum likelihood (ML) estimates for the survival curve. For interval-censored data, multiple curves maximize the likelihood, so two curves are produced that provide bounds on the ML estimated curves.

Parametric regression models. Regression models for interval-censored survival time data, due to computational issues, are primarily parametric (Hosmer, 2008). The *icenReg* package (Anderson-Bergman, 2017) also implements semi-parametric methods proposed by Pan (1999) and Wellner and Zhan (1997) that allow the use of the more familiar Cox proportional hazards regression model that was used to help assess the best functional form for parametric models.

Parametric regression models define the conditional survival function as:

$$S(t|\mathbf{X}, \boldsymbol{\beta}) = S_0(t)e^{\mathbf{X}^T\boldsymbol{\beta}},$$

where $\mathbf{X}$ is the matrix consisting of a set of covariates and $\boldsymbol{\beta}$ is a vector of regression parameters. $S_0(t)$ is the baseline survival function. Various distributions are proposed for the baseline function. We fit the model with choices available in the *icenReg* package and selected the distributions offering the best fit.

All surface materials, excluding only the two materials in Category 1 (with no observed PFU values at the first time point), were included in the regression analysis; 14 surface materials. A plot of the two curves (due to use of the Turnbull estimator for the baseline survival function estimates) for the Cox model, and three choices for the baseline distribution in a parametric model is shown in Figure 1. The semi-parametric estimate is a reasonable depiction of the data, accounting for the uncertainty due to interval censoring. Using the graphs and ML estimates, the lognormal distribution was chosen for the baseline model.

Results

Each material was tested in triplicate. The following data set is the average of infectious virus, presented as PFU/50μL at each time point (Table 2). One PFU is defined as one infectious viral particle.

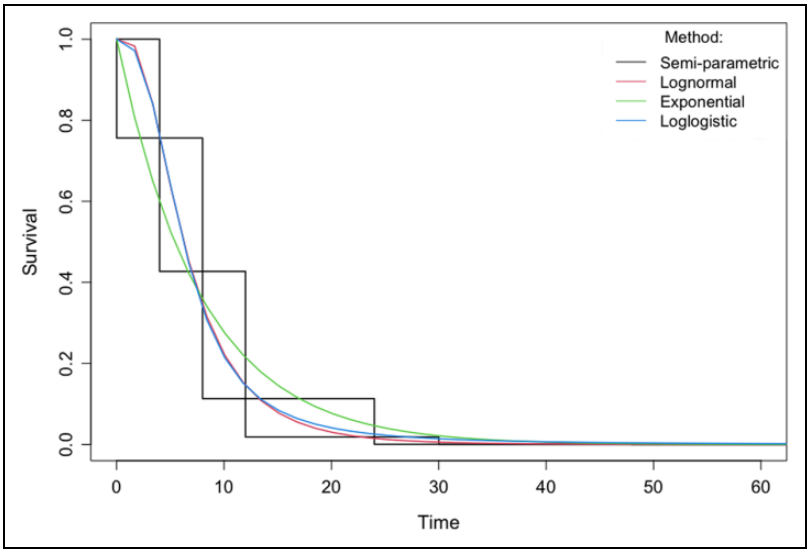

Figure 1. Plots of baseline survival functions for three parametric model choices and the semi-parametric Cox model, 14 materials.

Nonparametric Models

Overall surface materials. The nonparametric estimated survival curves for the entire data set of 16 materials are displayed in a range between two curves due to interval censoring that maximize the likelihood function. This range reflects that we do not know exactly where in the interval times infectious viral particles were no longer recovered from the surface. Two materials, copper sheet and solid surface with cupric oxide added, had no detectable infectious virus even at 4 hr. The other noteworthy feature of the overall data is the rapid degradation of most PFUs. By 24 hr, only three surfaces still had detectable infectious virus and by 48 hr, this went down to only one surface. No infectious virus remained on any surface hour 168 (7 days; Table 3).

Category of zero infectious particles by time. The observed data and resulting survival curve estimates appear to fall into several categories based on time to no recoverable virus (0 PFU) (Table 4 and Figure 2). At 4 hr, two materials (copper sheet and solid surface with cupric oxide) were excluded from subsequent analysis, as there were no infectious virus remaining by the first measurement time. At 8 hr, an additional four materials had no infectious viral particles detected. By 12 hr, 12 of the 16 surfaces had no infectious viral particles detected. The estimated nonparametric survival curves indicated that materials in this category exhibit some differences in estimated survival experience although they reach zero PFU by Hour 12 (see Table 2). The material with the most infectious virus in the group is stainless steel, brushed. At 4 hr, there were 495 infectious viral particles (4.95%) and at 8 hr, 130 infectious viral particles (1%). Other materials had lower percentages of detectable infectious virus. As an example, luxury vinyl tile #21 had only 1% at 4 hr remaining, and by 8 hr, 0.3%. Four materials had detectable infectious virus beyond 12 hr.

The estimated nonparametric survival curves indicate four materials exhibiting an extension of degradation as it takes longer for the surfaces to reach 0 PFUs. The four materials in Category 4 exhibit similar overall trends with a sharp decrease early. Acrylic solid surface demonstrates the slowest decrease among the materials; however, vinyl wall covering demonstrates a dramatic decrease between 0 and 4 hr and then a slowing rate of degradation to reach 0 infectious units.

Table 2. Infectious Virus at Each Time Point With a Starting Inoculate of 10,000 Plaque-Forming Units (PFUs) of SARS-CoV-2 in 50μL and Spread Evenly Across the 2 in.^{2} Surface. The Following Are the Calculated PFU per 50μL at Each Time Point for the Entire 2 in.^{2} Sample.

Description	4 hr	8 hr	12 hr	24 hr	30 hr	48 hr	168 hr
Acrylic solid surface	410 ± 3	295 ± 25	105 ± 11	21 ± 2	0	0	0
Solid surface with CuO	0	0	0	0	0	0	0
Stainless steel, brushed	495 ± 76	130 ± 57	0	0	0	0	0
High-pressure laminate	305 ± 118	0	0	0	0	0	0
Copper sheet	0	0	0	0	0	0	0
Quartz	330 ± 33	243 ± 3	106 ± 34	23 ± 12	0	0	0
Rubber flooring	390 ± 3	0	0	0	0	0	0
Vinyl, sheet, homogeneous	327 ± 25	57 ± 4	0	0	0	0	0
Wood laminate floor, commercial	245 ± 22	0	0	0	0	0	0
Luxury vinyl tile #15	242 ± 18	131 ± 29	90 ± 9	0	0	0	0
Luxury vinyl tile #21	100 ± 2	30 ± 5	0	0	0	0	0
Luxury vinyl tile #26	192 ± 2	5 ± 0	0	0	0	0	0
Carpet, commercial	115 ± 6	0	0	0	0	0	0
Carpet, residential	170 ± 20	12.5 ± 2	0	0	0	0	0
Upholstery, nonwoven	230 ± 40	45 ± 17	0	0	0	0	0
Vinyl wall covering, type II	195 ± 62	137 ± 6	100 ± 14	35 ± 7	12 ± 0	10 ± 2	0

Table 3. Summary Statistics of Plaque-Forming Units (PFUs) at Time Point (hr). [a]

	4 hr	8 hr	12 hr	24 hr	30 hr	48 hr
Median	265	20	0	0	0	0
Mean	234	69	25	4.9	0.7	0.6
Max (percent)	495 (4.95%)	295 (2.95%)	106 (1%)	35 (0.3%)	12 (0.1%)	10 (0.1%)
Materials at 0 PFU	2	6	12	13	15	15

[a] At 168 hr, no PFUs were detected, indicating no virus present.

Table 4. Categories of 16 Materials Based on Time to No Infectious Particles.

Category 1 4 hr	Category 2 8 hr	Category 3 12 hr	Category 4 After 12 hr
Solid surface with CuO	High-pressure laminate	Stainless steel, brushed	Acrylic solid surface
Copper sheet	Rubber flooring	Vinyl, sheet, homogeneous	Quartz
	Wood laminate flooring, commercial	Luxury vinyl tile #21	Vinyl wall covering, type II
	Carpet, nylon, commercial	Luxury vinyl Tile #26	Vinyl flooring #15
		Carpet, residential	
		Upholstery, nonwoven	

Regression Models

All surface materials, less the two materials in Category 1 (with no observed infectious virus at 4 hr), were included in the regression analysis. The fitted model using the loglogistic distribution is depicted graphically in Figure 3. Solid lines represent the estimated survival curve, dashed lines the associated 95% confidence intervals. The confidence intervals appear quite narrow due

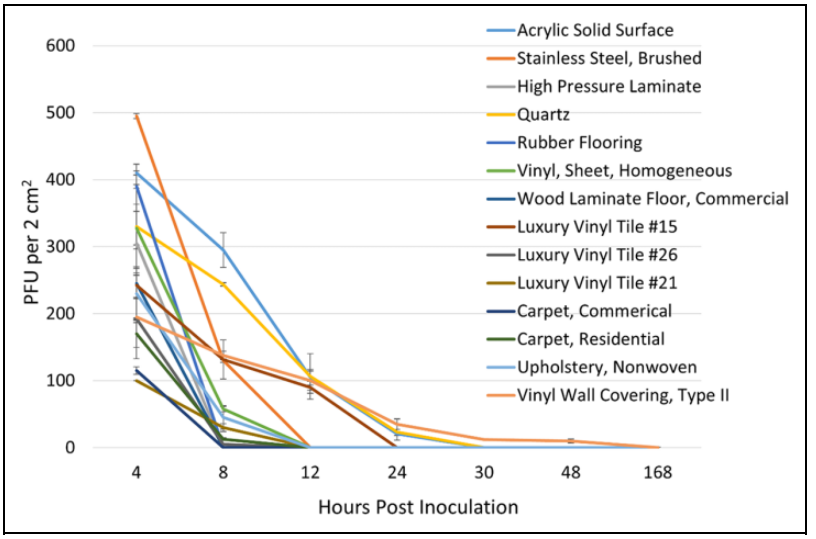

Figure 2. Viral decay by material over time.

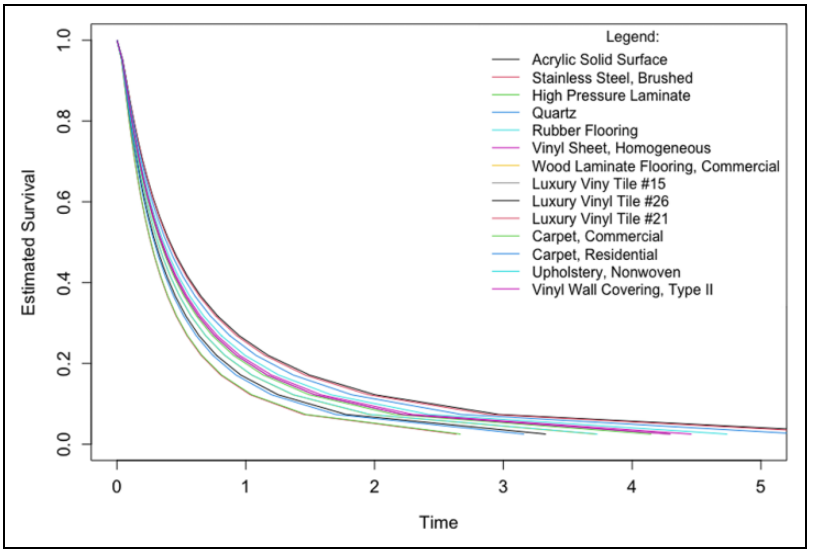

Figure 3. Plots of estimated survival functions (with confidence intervals, dashed lines) for loglogistic parametric model, 14 materials.

to the number of PFUs (10,000) coupled with data only at a small set of time points, and the scale of the graph with time extending beyond 50 hr.

We observe that the Category 4 groups are generally those with the slower rate of infectious virus decay. Acrylic solid surface had the longest overall survival times, followed by stainless steel, brushed and then quartz.

Parameter estimates for the full model are displayed in Table 5. The first two parameters (Mu and Log_s) are those of the lognormal baseline survival distribution. Both are significantly different from 0 suggesting two parameters are, in fact, useful for modeling the PFU.

Reference cell indicator coding was used with the acrylic solid surface, the material with the

Table 5. Summary of Parameter Estimates Lognormal Baseline Parametric Model, 14 Materials.

Parameter	Estimate[a]	Standard Error	HR	Category[b]	$T_{0.5}$[c]	$T_{0.1}$[c]
Mu (baseline lognormal mean)	−1.086	.024				
Log_s (baseline lognormal *SD*)	0.251	.009				
Acrylic solid surface	Reference[d]		1.00	4	.81	2.57
Stainless steel, brushed	0.015	.012	1.015	3	.80	2.54
Quartz	0.056	.012	1.057	4	.78	2.38
Rubber flooring	0.110	.012	1.116	2	.75	2.23
Vinyl sheet, homogeneous	0.140	.012	1.150	4	.74	2.15
Vinyl wall covering, type II	0.157	.012	1.170	4	.73	2.09
Luxury vinyl tile #15	0.158	.012	1.172	4	.73	2.08
High-pressure laminate	0.175	.012	1.192	2	.72	2.06
Upholstery, nonwoven	0.228	.013	1.257	3	.70	1.93
Wood laminate flooring, commercial	0.231	.013	1.259	2	.70	1.93
Luxury vinyl tile #26	0.286	.013	1.331	3	.67	1.81
Carpet, residential	0.313	.014	1.367	3	.66	1.75
Carpet, commercial	0.403	.015	1.496	2	.62	1.59
Luxury vinyl tile #21	0.410	.015	1.507	3	.62	1.58

[a] All parameter estimates were statistically significant, $p < .001$.
[b] Category 4: detectable virus past 12 hr, Category 3: 0 detectable virus starting at time 12 hr, Category 2: 0 detectable virus starting at 8 hr.
[c] $T_{0.5}$ = estimated time to reach 0.5 (50%, 5,000) of plaque-forming units (PFU) on surface and $T_{0.1}$ = time to reach 1,000 PFU (10%).
[d] The acrylic solid surface was used as the reference group with reference cell coding used.

slowest decaying survival function, as the reference group. The positive values for the parameters estimates of other materials reflect the faster estimated rates of decay in PFU.

As with other survival models, the hazard ratio (HR) is computed by exponentiating the parameter estimates. For materials other than the reference material, the HR compares that material to acrylic solid surface. For example, the HR of 1.5 for luxury vinyl tile #21 suggests that the rate of decay in total PFU on this surface is 1.5 times as fast as on the acrylic solid surface.

In this model, all parameter estimates were statistically significant ($p < .001$), giving evidence that there are differences in survival curves between different materials. The last two columns of Table 5 are estimated times, based on the model, when a material reaches 50% of the starting amount ($T_{0.5}$) and below 1,000 ($T_{0.1}$) PFU. The model estimates no material taking more than 1 hr to reduce the PFU amount by 50%. This reflects the fact that all 16 materials, including the additional 2 materials in Category 1 not modeled, were well below 50% by 4 hr. In fact, the largest average percent of infectious virus remaining on a surface at 4 hr was approximately 5%.

We see that all materials are estimated to take less than around two and a half hours to degrade to 1,000 PFUs (10% remaining). Again, Table 2 describes that the maximum amount remaining on one of the surfaces at 4 hr was around 500, reflecting the data observed.

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While the parameters in the model were statistically significant, they are based on comparisons to the reference group. Pairwise comparisons (adjusting for multiple comparisons) of materials to those with the most similar estimates reveals that there are many with survival experiences that are not statistically different. All other pairs are statistically different with p values < .0001.

The groups of materials that are statistically indistinguishable are depicted in Table 6. Groups

Table 6. Groups of Materials With Statistically Similar Survival Curves.

Group 1	Group 2	Group 3	Group 4	Group 5
Stainless steel, brushed	Vinyl wall covering, type II	Upholstery, nonwoven	Luxury vinyl tile #26	Carpet, nylon, commercial
Acrylic solid surface	Vinyl flooring #15	Wood laminate flooring, commercial	Carpet, residential	Luxury vinyl tile #21
	High-pressure laminate			
$p = .376$	$p = .238, .321, .759$[a]	$p = .272$	$p = .082$	$p = .930$

[a]Three pairwise comparisons were required for the three materials in the group.

and materials are presented in the order of the table depicting the model, from longest to shortest survival. As illustration, for the pair of materials in Group 3 of the table, the estimated HR comparing nonwoven upholstery and commercial wood laminate flooring is 1.015 ($SE = 0.014$) with a p value of .272. The estimated HR is very near one, and the lack of a difference in survival for these two materials is displayed in Figure 4 by the large overlap in confidence intervals for the estimated curves.

Discussion

Several previous studies have evaluated stability of SARS-CoV-2 on common surface materials via environmental sampling or inoculation studies under variable conditions (Cheng et al., 2020; Chia et al., 2020; Chin et al., 2020; Guo et al., 2020; Ong et al., 2020; Rubens et al., 2020; Santarpia et al., 2020; van Doremalen et al., 2020). These studies provided valuable information but posed important questions about the relevance of surface-related transmission, as many of these studies focused on viral detection by PCR. To increase our understanding of viral survival on various surfaces over time, we inoculated 16 different surfaces with a known amount of SARS-CoV-2 and evaluated infectious virus survival over a period of 7 days by standard plaque assay. Plaque assays are the most appropriate method for this analysis, as they evaluate infectious virus, while PCR only detects viral genetic components that do not directly translate to infectious virus particles. In fact, several studies exist to suggest that a positive PCR value does not indicate an active infection since viral nucleic acids are detected for much longer than infectious particles (Bullard et al., 2020; Krupp et al., 2020; Liu et al., 2020).

Plaque assays are the most appropriate method for this analysis, as they evaluate infectious virus, while PCR only detects viral genetic components that do not directly translate to infectious virus particles.

As professionals continue to evaluate ways to break the transmission cycles, teams have identified important information about droplets generated from infected individuals. For example, talking for 1 min may produce 1,000 virions that can remain airborne for several minutes (Stadnytskyi et al., 2020), coughing can produce 3,000 droplets and sneezing produces up to 40,000 droplets. Larger droplets contain more virions that do not travel as far as microdroplets but can be more environmentally stable from the protection provided by the droplet size and are very relevant to contact transmission via surfaces (Cole & Cook, 1998; Dhand & Li, 2020; Duguid, 1945).

The inoculation dose of 10,000 PFU/2 in.^{2} used in this study represented a reasonable surface inoculation by an infectious individual within a 6 ft. perimeter over 10 min. Once droplets settle, their importance in respiratory transmission wanes while fomite transmission becomes more important. Work has shown that viral infectivity reduces over time when on surfaces (Ben-Shmuel et al., 2020) though this is compounded by instinctive face-touching which

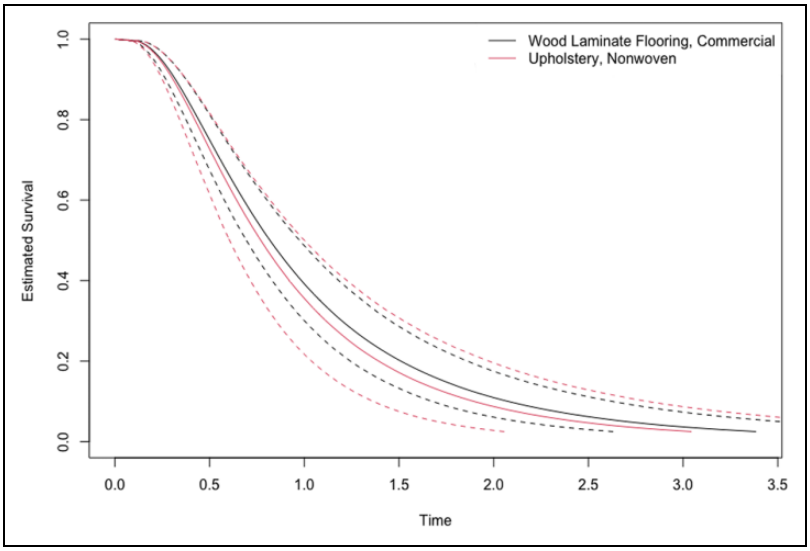

Figure 4. Survival curve estimates with 95% confidence intervals for wood laminate flooring, commercial and, upholstery, nonwoven.

increases the number of potential exposure events (Senthilkumaran et al., 2020). Although hands are responsible for the spread of most infectious diseases, there is little information regarding infectious dose of fomites or touch for coronaviruses.

The persistence of SARS-CoV-2 on surfaces is well documented with sinks and hand sanitizer bottles being to most likely to be contaminated of touchable surfaces (Ben-Shmuel et al., 2020; Razzini et al., 2020; Senthilkumaran et al., 2020). While virus was detected at less than 5% of the initial dose, recovery of any live virus may potentially establish an infection (Flint et al., 2020). The infectious dose of a virus represents the average number of virions needed to cause disease in at least 50% of exposed individuals. There is significant variability regarding susceptibility and permissiveness of specific individuals to a virus such that the establishment of infection can occur from a single virion up to the maximum infectious dose (Schröder, 2020). Previous studies estimated the average infectious dose of coronaviruses to be 10^7 PFU although many researchers defer to work on influenza with an average infectious dose of 1,000 PFU (Evans, 2020; Watanabe et al., 2010). Without knowing the true infectious dose of SARS-CoV-2, a conservative approach may be to consider that one infectious viral particle is enough to initiate an infection. Thus, the risk of transmission by surface contamination in indoor environments should be mitigated with procedures to decontaminate the indoor environment and increase diligence for hand hygiene and personal protective equipment (PPE; Carraturo et al., 2020; Cheng et al., 2020; Korber et al., 2020; WHO, 2020; Yang, 2020).

It is interesting to note that the HR values, displayed from smallest to largest (see Table 5), do not completely align with the grouping categories of time to zero infectious virus. For example, luxury vinyl tile #15 is in Category 4, meaning infectious virus is present beyond 8 hr (average of 90 at 12 hr, 0 starting at 24 hr). The stainless steel, brushed surface is in Category 3, meaning it had 0 infectious virus by Hour 12. However, the stainless steel, brushed HR is smaller (1.015 compared to 1.172 for luxury vinyl tile #15) meaning a slower estimated rate of PFU loss. The reason is that the luxury vinyl tile #15 dropped to a lower viral titer by 4 hr (average of 240 compared to 495 for the stainless steel), and while there were still infectious particles remaining at 12 hr, the numbers by 4 hr are small enough that the survival curve for luxury vinyl tile #15 is

estimated to be steeper and reaching a flattening off point more rapidly. The counts at 12 hr had less impact on the estimates, in part because they represent a very small amount remaining on the luxury vinyl tile #15; average of 90 PFU or 0.9%.

Vinyl wall covering, type II is another interesting example since it has infectious virus detectable as long as 48 hr, the longest of any surface. However, there are five materials, acrylic solid surface through vinyl sheet homogeneous, with survival curves that are estimated to lose PFU more slowly. The reason is that vinyl wall covering, type II dropped to only an average of 195 PFU (1.95%) at the first time point (4 hr). The other materials were higher at that point (acrylic solid surface, e.g., at 410 PFU). Thus, the vinyl wall covering, type II curve descends more rapidly initially before leveling off and is to the left of the other two (as shown in Figure 2). While the decay is nearly complete and quite rapid for this material, small amounts of infectious virus are still observed for longer than on other materials.

We discuss issues with the precision of estimates due to the time points for collecting data in the Limitations section. Thus, it is more useful to consider materials in terms of their practical differences in this study. For example, materials such as vinyl, sheet, homogeneous and rubber flooring are statistically different but have similar HRs when compared to the reference material of acrylic solid surface (1.116 and 1.15, respectively). Further, the estimated times to 50% reduction of infectious virus and to 1,000 PFU are close enough to be considered practically similar (0.75 hr compared to 0.74 for the 50% times as an example).

While studies with other coronaviruses are not directly comparable to these results, a similar study with an alpha-coronavirus reflects our data showing that virus is inactivated rapidly on copper surfaces but persists on stainless steel (Warnes et al., 2015). Warnes et al. (2015) also showed inactivation of coronavirus on silicon rubber which is a synthetic elastomer, not comparable to the rubber flooring used in this study. Warnes et al. (2015) utilized 304 stainless steel, which is of the same composition as the samples for this study but did not specify the finish. This study utilized 304 stainless steel finish #4 brushed, which is the most common stainless steel used in architectural applications, equipment, and furniture components (Warnes et al., 2015). However, taken together, the data from this study and Warnes et al. (2015) suggest that stainless steel may not be the most appropriate surface material for products used in areas where there is a concerted effort to minimize levels of contamination.

High touch and less frequently touched surface materials have commonalities in material attributes but may differ in exposure risk. However, researchers evaluating floor contamination found high-touch objects (e.g., clothing, cell phone chargers, call buttons, blood pressure cuffs, and bed linens) in occupied hospital patient rooms in contact with the floor in 41% of the rooms with 29% of cultured samples found to be contaminated suggesting that transmission of contaminants from non-high-touch objects to high-touch objects is common (Deshpande et al., 2017).

High touch and less frequently touched surface materials have commonalities in material attributes but may differ in exposure risk.

Another example of the potential of non-high-touch objects contributing to risk of exposure is a study that focused on surface contamination of the COVID-19 virus in hospital patient units that found 81% of surfaces tested were positive for the virus, including high-touch surfaces, window ledges, and ICU workers' shoes (Guo et al., 2020). The combination of gravity and air flow contributes to virus droplets to land on surfaces, including the floor and may increase changes in direction of droplets with high air changes required for the healthcare environment. The contamination on healthcare staff shoes and tracing areas of the hospital that were off-limits to patients such as the pharmacy indicate that healthcare workers are potentially carriers of the virus and may transmit viral particles throughout the healthcare facility via the soles of their shoes unless protocols are implemented to disinfect

shoe soles prior to leaving areas containing COVID-19 patients.

. . . healthcare workers are potentially carriers of the virus and may transmit viral particles throughout the healthcare facility via the soles of their shoes.

Strengths and Limitations

This study was completed under laboratory conditions and is not directly translatable to transmission in the built environment; however, it creates a decay curve that allows us to understand virus stability on a variety of indoor surface materials.

We alluded to issues with the models and data in the results. Essentially, the primary issue is with the measurement time points. For most materials, the PFU counts reached zero within only a few time points, so we lack a large amount of data and information on their survival experience. Two materials were excluded from the regression modeling entirely as the PFU count was zero by the first time point, leaving no data available for analysis. However, several other materials had only one or two time points before reaching zero.

The data issue has several ramifications. One issue is in the choice for the statistical model, as several baseline hazard function choices were similar statistically. More data are needed to determine the best function to use. Additionally, while the model exhibits reasonable fit, the lack of data in early time points reduces the precision of estimation for the survival curves. Thus, results for which materials differ and which do not must be further studied. Further, we are unable to get a precise estimate of survival time for infectious virus. Our estimates of the time to 50% and 90% remaining are reasonable for the data, but in both cases are less than 4 hr, the first observation point. With measurements at intermediate times like 1, 2, and 3 hr, for example, we would have more precision and confidence in those values.

Despite these limitations, the models presented offer positives. The model is conservative in terms of estimates of the survival time—essentially, estimating longer survival, if anything, particularly for the median remaining PFU values. While we cannot fully rely on the statistical tests to determine which materials differ, the model does provide insight about the survival experience and begins to estimate how much this varies by material. We also identify some materials that appear to offer better results than others, though more study is needed to truly confirm significant differences in indoor surface materials influence on the virus.

Finally, the approach presented is a potential methodology worth utilizing in further studies. The model allowed for imprecision in terms of knowing the exact time an infectious particle disappears from the surface by modeling the data as interval censored.

Recommendations for Future Research

It is critical to increase understanding about the viral kinetics and transmission feasibility in the built environment affected by this highly contagious virus. Future laboratory experiments would benefit from an increased number of time points earlier in the timeline to increase sensitivity, since the virus decays rapidly. Increasing the number of specimens for each material type tested is also recommended. Additional research is needed to assess SARS-CoV-2 transmission and viability in an uncontrolled environment, including healthcare facilities, educational facilities, residences, and other building typologies where the virus may dwell.

Conclusion

Indoor environmental surface materials may be vectors of transmission when contaminated with infectious agents such as SARS-CoV-2. In this study, virus inoculated on common indoor environmental surface materials decayed rapidly, with most surface materials tested clear of the live virus by 12 hr. The CDC (2020a) have provided guidance for cleaning and disinfecting with specific strategies. The findings from this research supports the disinfection recommendations by the CDC. There is much to learn about the virus and how material composition and disinfection may mitigate contamination of surface materials to reduce risk of exposure; however, this study

suggests that the virus has a relatively short life span. Increasing disinfection of surfaces within the 12- to 24-hr time frame is recommended; material selection should focus on material composition and detailing to maintain integrity over the life span of the surface material. The risk of transmission by surface contamination in indoor environments should be mitigated with procedures to decontaminate the indoor environment, disrupting the infection cycle and increase diligence for hand hygiene and PPE. Epidemiological studies are critical to understand how surfaces play a role in SARS-CoV-2 transmission.

Implications for Practice

- While most surfaces are not conducive to long-term viral survival, these data highlight the need to properly and frequently disinfected surfaces, thereby preventing additional transmission.
- Results of the flooring samples do not indicate that carpet poses an extra hazard for viral transmission.
- Copper sheet and solid surface with cupric oxide samples did not maintain infectious virus at the first time point of 4 hr, indicating that the material was effective in actively decreasing the viral load.

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