

CORRESPONDENCE

Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1

TO THE EDITOR: A novel human coronavirus that is now named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (formerly called HCoV-19) emerged in Wuhan, China, in late 2019 and is now causing a pandemic.¹ We analyzed the aerosol and surface stability of SARS-CoV-2 and compared it with SARS-CoV-1, the most closely related human coronavirus.²

We evaluated the stability of SARS-CoV-2 and SARS-CoV-1 in aerosols and on various surfaces and estimated their decay rates using a Bayesian regression model (see the Methods section in the Supplementary Appendix, available with the full text of this letter at NEJM.org). SARS-CoV-2 nCoV-WA1-2020 (MN985325.1) and SARS-CoV-1 Tor2 (AY274119.3) were the strains used. Aerosols (<5 μm) containing SARS-CoV-2 ($10^{5.25}$ 50% tissue-culture infectious dose [TCID₅₀] per milliliter) or SARS-CoV-1 ($10^{6.75-7.00}$ TCID₅₀ per milliliter) were generated with the use of a three-jet Collision nebulizer and fed into a Goldberg drum to create an aerosolized environment. The inoculum resulted in cycle-threshold values between 20 and 22, similar to those observed in samples obtained from the upper and lower respiratory tract in humans.

Our data consisted of 10 experimental conditions involving two viruses (SARS-CoV-2 and SARS-CoV-1) in five environmental conditions (aerosols, plastic, stainless steel, copper, and cardboard). All experimental measurements are reported as means across three replicates.

SARS-CoV-2 remained viable in aerosols throughout the duration of our experiment (3 hours), with a reduction in infectious titer from $10^{3.5}$ to $10^{2.7}$ TCID₅₀ per liter of air. This reduction was similar to that observed with SARS-CoV-1, from $10^{4.3}$ to $10^{3.5}$ TCID₅₀ per milliliter (Fig. 1A).

SARS-CoV-2 was more stable on plastic and stainless steel than on copper and cardboard, and viable virus was detected up to 72 hours after application to these surfaces (Fig. 1A), although the virus titer was greatly reduced (from $10^{3.7}$ to

$10^{0.6}$ TCID₅₀ per milliliter of medium after 72 hours on plastic and from $10^{3.7}$ to $10^{0.6}$ TCID₅₀ per milliliter after 48 hours on stainless steel). The stability kinetics of SARS-CoV-1 were similar (from $10^{3.4}$ to $10^{0.7}$ TCID₅₀ per milliliter after 72 hours on plastic and from $10^{3.6}$ to $10^{0.6}$ TCID₅₀ per milliliter after 48 hours on stainless steel). On copper, no viable SARS-CoV-2 was measured after 4 hours and no viable SARS-CoV-1 was measured after 8 hours. On cardboard, no viable SARS-CoV-2 was measured after 24 hours and no viable SARS-CoV-1 was measured after 8 hours (Fig. 1A).

Both viruses had an exponential decay in virus titer across all experimental conditions, as indicated by a linear decrease in the log₁₀ TCID₅₀ per liter of air or milliliter of medium over time (Fig. 1B). The half-lives of SARS-CoV-2 and SARS-CoV-1 were similar in aerosols, with median estimates of approximately 1.1 to 1.2 hours and 95% credible intervals of 0.64 to 2.64 for SARS-CoV-2 and 0.78 to 2.43 for SARS-CoV-1 (Fig. 1C, and Table S1 in the Supplementary Appendix). The half-lives of the two viruses were also similar on copper. On cardboard, the half-life of SARS-CoV-2 was longer than that of SARS-CoV-1. The longest viability of both viruses was on stainless steel and plastic; the estimated median half-life of SARS-CoV-2 was approximately 5.6 hours on stainless steel and 6.8 hours on plastic (Fig. 1C). Estimated differences in the half-lives of the two viruses were small except for those on cardboard (Fig. 1C). Individual replicate data were noticeably “noisier” (i.e., there was more variation in the experiment, resulting in a larger standard error) for cardboard than for other surfaces (Fig. S1 through S5), so we advise caution in interpreting this result.

We found that the stability of SARS-CoV-2 was similar to that of SARS-CoV-1 under the experimental circumstances tested. This indicates that differences in the epidemiologic characteristics of these viruses probably arise from other factors, including high viral loads in the upper

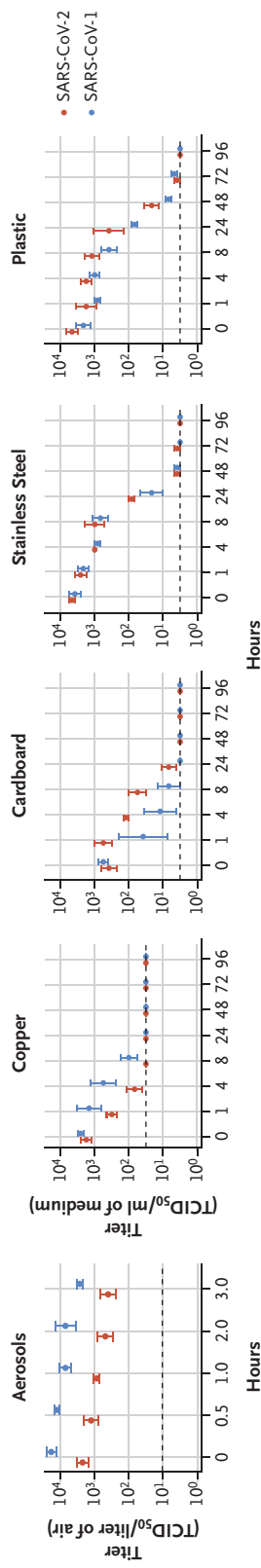
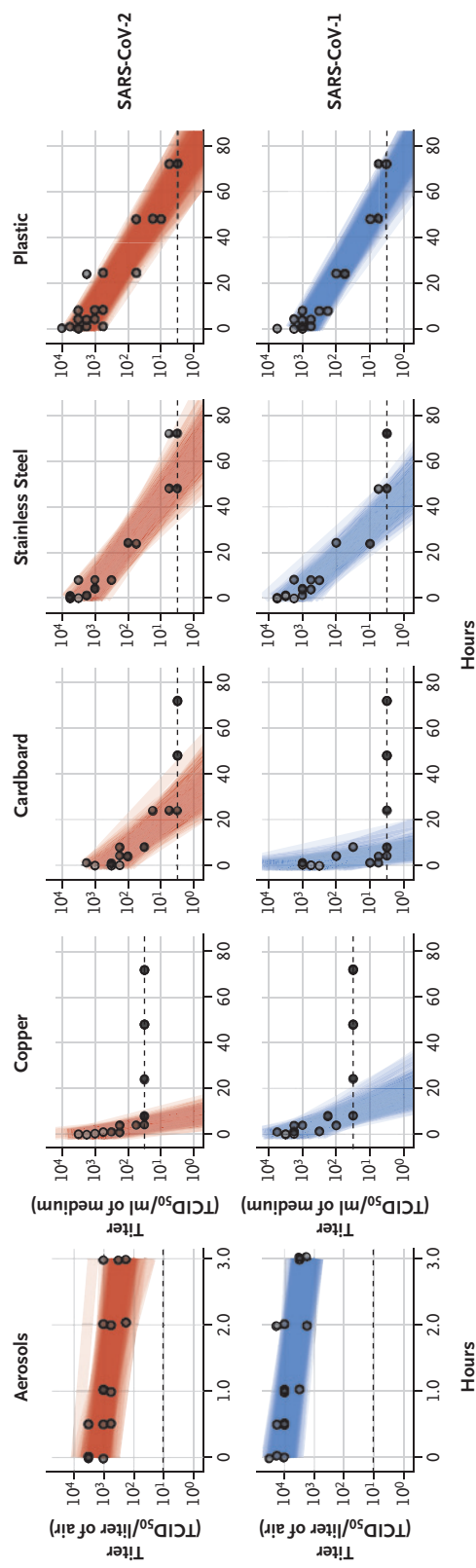
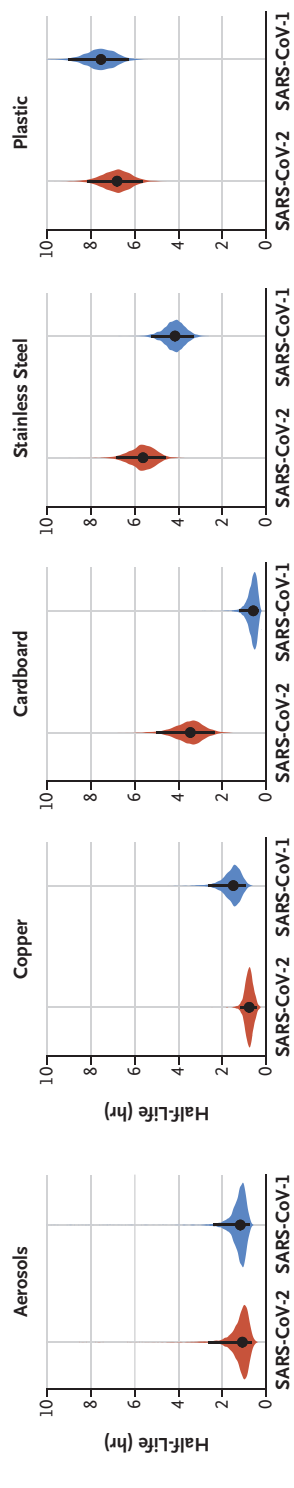
A Titers of Viable Virus**B** Predicted Decay of Virus Titer**C** Half-Life of Viable Virus

Figure 1 (facing page). Viability of SARS-CoV-1 and SARS-CoV-2 in Aerosols and on Various Surfaces.

As shown in Panel A, the titer of aerosolized viable virus is expressed in 50% tissue-culture infectious dose (TCID₅₀) per liter of air. Viruses were applied to copper, cardboard, stainless steel, and plastic maintained at 21 to 23°C and 40% relative humidity over 7 days. The titer of viable virus is expressed as TCID₅₀ per milliliter of collection medium. All samples were quantified by end-point titration on Vero E6 cells. Plots show the means and standard errors (I bars) across three replicates. As shown in Panel B, regression plots indicate the predicted decay of virus titer over time; the titer is plotted on a logarithmic scale. Points show measured titers and are slightly jittered (i.e., they show small rapid variations in the amplitude or timing of a waveform arising from fluctuations) along the time axis to avoid overplotting. Lines are random draws from the joint posterior distribution of the exponential decay rate (negative of the slope) and intercept (initial virus titer) to show the range of possible decay patterns for each experimental condition. There were 150 lines per panel, including 50 lines from each plotted replicate. As shown in Panel C, violin plots indicate posterior distribution for the half-life of viable virus based on the estimated exponential decay rates of the virus titer. The dots indicate the posterior median estimates, and the black lines indicate a 95% credible interval. Experimental conditions are ordered according to the posterior median half-life of SARS-CoV-2. The dashed lines indicate the limit of detection, which was $3.33 \times 10^{0.5}$ TCID₅₀ per liter of air for aerosols, $10^{0.5}$ TCID₅₀ per milliliter of medium for plastic, steel, and cardboard, and $10^{1.5}$ TCID₅₀ per milliliter of medium for copper.

respiratory tract and the potential for persons infected with SARS-CoV-2 to shed and transmit the virus while asymptomatic.^{3,4} Our results indicate that aerosol and fomite transmission of SARS-CoV-2 is plausible, since the virus can remain viable and infectious in aerosols for hours and on surfaces up to days (depending on the inoculum shed). These findings echo those with SARS-CoV-1, in which these forms of transmission were associated with nosocomial spread and super-spreading events,⁵ and they provide information for pandemic mitigation efforts.

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The findings and conclusions in this letter are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention (CDC). Names of specific vendors, manufacturers, or products are included for public health and informational purposes; inclusion does not imply endorsement of the vendors, manufacturers, or products by the CDC or the Department of Health and Human Services.

Supported by the Intramural Research Program of the National Institute of Allergy and Infectious Diseases, National Institutes of Health, and by contracts from the Defense Advanced Research Projects Agency (DARPA PREEMPT No. D18AC00031, to Drs. Lloyd-Smith and Gamble), from the National Science Foundation (DEB-1557022, to Dr. Lloyd-Smith), and from the Strategic Environmental Research and Development Program of the Department of Defense (SERDP, RC-2635, to Dr. Lloyd-Smith).

Disclosure forms provided by the authors are available with the full text of this letter at NEJM.org.

This letter was published on March 17, 2020, at NEJM.org.

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DOI: 10.1056/NEJMc2004973

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Supplementary Appendix

This appendix has been provided by the authors to give readers additional information about their work.

Supplement to: van Doremalen N, Bushmaker T, Morris DH, et al. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N Engl J Med. DOI: 10.1056/NEJMc2004973

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Supplemental methods

Laboratory experiments

Viruses and titration

HCoV-19 nCoV-WA1-2020 (MN985325.1) (Holshue et al., 2020) and SARS-CoV-1 Tor2 (AY274119.3) (Marra et al., 2003) were the strains used in our comparison. Viable virus in all surface and aerosol samples was quantified by end-point titration on Vero E6 cells as described previously (van Doremalen et al., 2013).

Virus stability in aerosols

Virus stability in aerosols was determined as described previously at 65% relative humidity (RH) and 21-23°C (Fischer et al., 2016). In short, aerosols (<5 µm) containing HCoV-19 ($10^{5.25}$ TCID₅₀/mL) or SARS-CoV-1 ($10^{6.75-7}$ TCID₅₀/mL) were generated using a 3-jet Collison nebulizer and fed into a Goldberg drum to create an aerosolized environment. Aerosols were maintained in the Goldberg drum and samples were collected at 0, 30, 60, 120 and 180 minutes post-aerosolization on a 47mm gelatin filter (Sartorius). Filters were dissolved in 10 mL of DMEM containing 10% FBS. Three replicate experiments were performed.

Virus stability on surfaces

Surface stability was evaluated on plastic (polypropylene, ePlastics), AISI 304 alloy stainless steel (Metal Remnants), copper (99.9%) (Metal Remnants) and cardboard (local supplier) representing a variety of household and hospital situations and was performed as described previously at 40% RH and 21-23°C using an inoculum of 10^5 TCID₅₀/mL (van Doremalen et al., 2013). This inoculum resulted in cycle-threshold values (Ct) between 20 and 22 similar to those observed in samples from human upper and lower respiratory tract (Zou et al., 2020). In short, 50 µl of virus was deposited on the surface and recovered at predefined time-points by adding 1 mL of DMEM. Stability on cardboard was evaluated by depositing 50 µl of virus on the surface and recovering the inoculum by swabbing of the surface, the swab was deposited 1 mL of DMEM. Three replicate experiments were performed for each surface.

Statistical analyses

Bayesian regression model description

The durations of detectability depend on initial inoculum and sampling method, as expected. To evaluate the inherent stability of the viruses, we estimated the decay rates of viable virus titers using a Bayesian regression model. This modeling approach allowed us to account for differences in initial inoculum levels across replicates, as well as interval-censoring of titer data and other sources of experimental noise. The model yields estimates of posterior distributions of viral decay rates and half-lives in the various experimental conditions – that is, estimates of the range of plausible values for these parameters given our data, with an estimate of the overall uncertainty (Gelman et al., 2013).

In the model notation that follows, the symbol $\sim$ denotes that a random variable is distributed according to the given distribution. Normal distributions are parametrized as Normal(mean, standard deviation). Positive-constrained normal distributions (“Half-Normal”) are parametrized as Half-Normal(mode, standard deviation). We use $\langle \text{Distribution Name} \rangle \text{CDF}(x, \text{parameters})$ to denote the cumulative distribution function of a probability distribution, so for example NormalCDF(5, 0, 1) is the value of the Normal(0, 1) cumulative distribution function at 5.

Our data consist of 10 experimental conditions: 2 viruses (HCoV-19 and SARS-CoV-1) by 5 environmental conditions (aerosols, plastic, stainless steel copper and cardboard). Each has three replicates, and multiple time-points for each replicate. We analyze the two viruses separately. For each, we denote by y_{ijk} the measured $\log_{10}$ titer in experimental condition i during replicate j at time-point k . To construct our likelihood function, we need to know the probability of observing a given $\log_{10}$ titer measurement y_{ijk} given values of the parameters.

Because our titer data are estimated and recorded in increments of $1/n_{\text{wells}} \log_{10} \text{TCID}_{50}/\text{mL}$, where n_{wells} is the number of wells used for endpoint titration, our $\log_{10}$ titer values are interval-censored – only known to within a range of width $1/n_{\text{wells}}$. In addition, there is a degree of measurement noise in the titration process itself.

To model this, we assume that in each experimental condition i , there is a true underlying $\log_{10}$ titer x_{ijk} that is measured with some amount of experimental noise or error ε_{ijk} and then observed as an interval-censored value $y_{ijk} \approx x_{ijk} + \varepsilon_{ijk}$. We model the measurement errors ε_{ijk} as Normally distributed with a standard deviation σ_i that is shared by all samples in the given experimental condition; this reflects the fact that some experimental setups may be more or less noisy than others.

69 $\varepsilon_{ijk} \sim \text{Normal}(0, \sigma_i)$

70 We model the probability of observing an interval-censored $\log_{10}$ titer value y_{ijk} given a true underlying
 71 $\log_{10}$ titer x_{ijk} and a measurement error standard deviation σ_i as:

72
$$P(y_{ijk} | x_{ijk}, \sigma_i) = \text{NormalCDF}(y_{ijk}, x_{ijk}, \sigma_i) - \text{NormalCDF}(y_{ijk} - 1/n_{\text{wells}}, x_{ijk}, \sigma_i)$$

73 This reflects the probability given a true value x_{ijk} plus the measurement error $x_{ijk} + \varepsilon_{ijk}$ falls between
 74 $y_{ijk} - 1/n_{\text{wells}}$ and y_{ijk} . Due to the $\log_{10}$ titer imputation technique used, a titer in that range is most likely to
 75 be rounded up and reported as y_{ijk} .

76 The detection limit of our experiment is $0.5 \log_{10}$ TCID₅₀/mL. The probability of observing an
 77 undetectable measured $\log_{10}$ titer value y_{ijk} given a true $\log_{10}$ titer value x_{ijk} is given by:

78
$$P(y_{ijk} \leq 0.5 | x_{ijk}, \sigma_i) = \text{NormalCDF}(0.5, x_{ijk}, \sigma_i)$$

79 We then model each replicate j for experimental condition i as starting with some true initial $\log_{10}$ titer
 80 $x_{ij}(0) = x_{ij0}$. We assume that viruses in experimental condition i decay exponentially at a rate λ_i over time t .
 81 It follows that

82
$$x_{ij}(t) = x_{ij0} - \lambda_i t$$

83 where t_k is the k^{th} measured time-point.

84 Model prior distributions

85 We place a weakly informative Normal prior distribution on the initial $\log_{10}$ titers x_{ij0} to rule out
 86 implausibly large or small values (e.g. in this case undetectable $\log_{10}$ titers or $\log_{10}$ titers much higher than
 87 the deposited concentration), while allowing the data to determine estimates within plausible ranges:

88
$$x_{ij0} \sim \text{Normal}(4.5, 2.5)$$

89 We likewise placed a weakly informative Half-Normal prior on the exponential decay rates λ_i :

90
$$\lambda_i \sim \text{Half-Normal}(0.5, 4)$$

We placed a weakly informative Half-Normal prior on the standard deviations of the experimental error distributions σ_i :

$$\sigma_i \sim \text{Half-Normal}(0, 2)$$

Markov Chain Monte Carlo Methods

We drew posterior samples using Stan, which implements a No-U-Turn Sampler (a form of Markov Chain Monte Carlo). We ran four replicate chains from random initial conditions for 2000 iterations, with the first 1000 iterations as a warmup/adaptation period. We saved the final 1000 iterations from each chain, giving us a total of 4000 posterior samples. We assessed convergence by inspecting trace plots and examining $\hat{R}$ and effective sample size (n_{eff}) statistics ($\hat{R}$ for all parameters ≤ 1.003 , n_{eff} for all parameters $\geq 28\%$ of total samples).

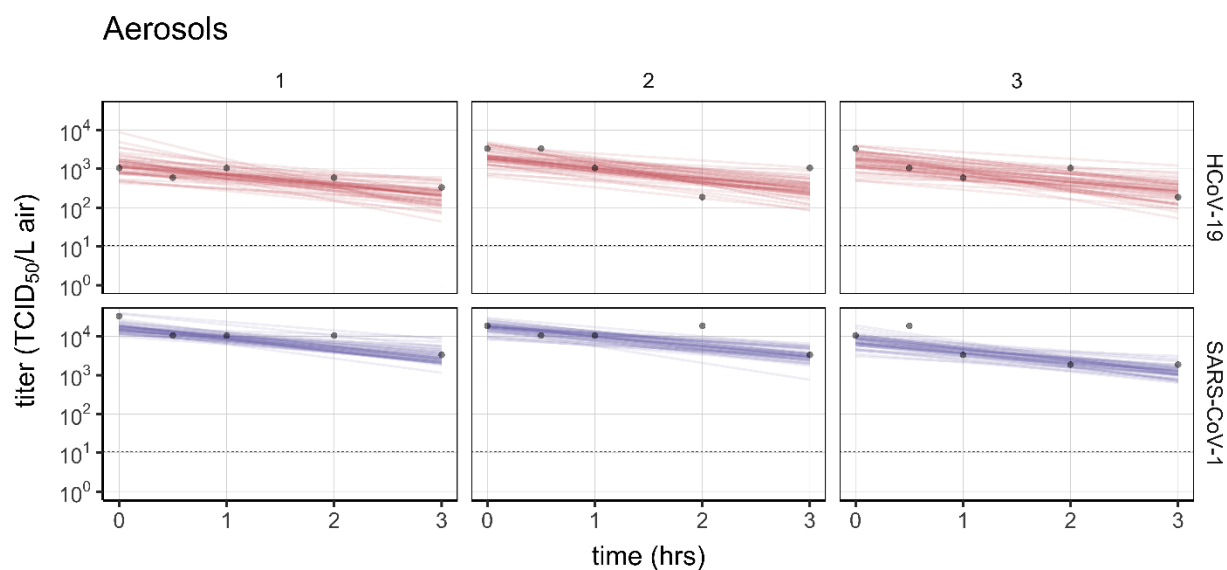
Supplemental table and figures

Table 1. Posterior median estimates and 95% credible intervals (2.5%–97.5% quantile range) for half-lives of HCoV-19 and SARS-CoV-1 in aerosols and on various surfaces, as well as a median estimate and 95% credible interval for the difference between the two half-lives (HCoV-19 – SARS-CoV-1).

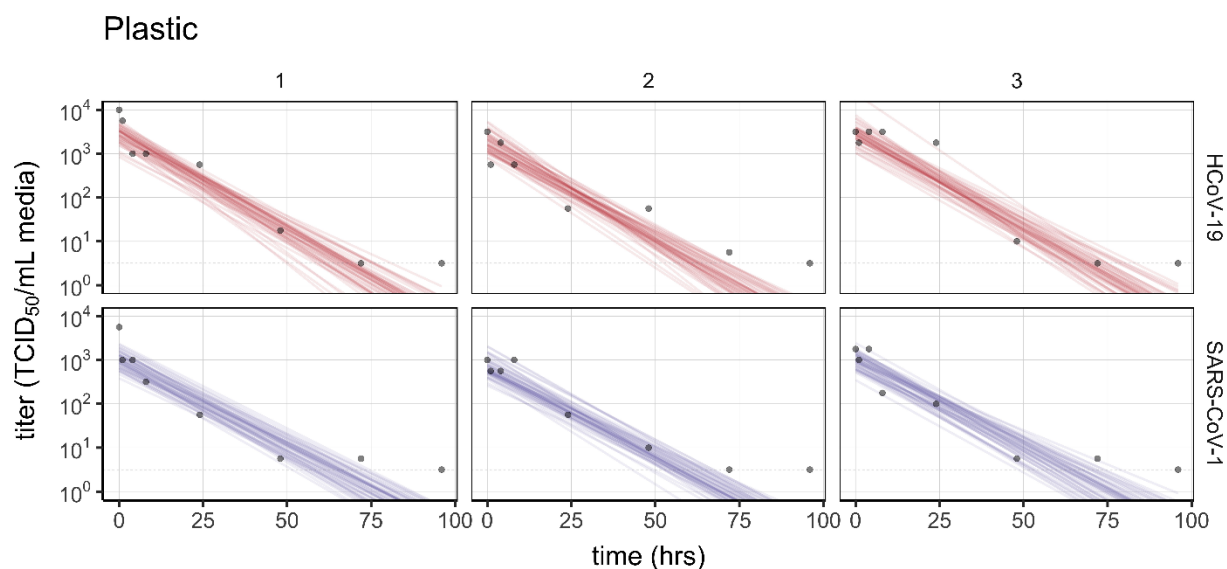
	HCoV-19			SARS-CoV-1			HCoV-19 – SARS-CoV-1		
	half-life (hrs)			half-life (hrs)			difference (hrs)		
<i>Material</i>	<i>median</i>	<i>2.5%</i>	<i>97.5%</i>	<i>median</i>	<i>2.5%</i>	<i>97.5%</i>	<i>median</i>	<i>2.5%</i>	<i>97.5%</i>
Aerosols	1.09	0.64	2.64	1.18	0.778	2.43	-0.0913	-1.35	1.39
Copper	0.774	0.427	1.19	1.5	0.929	2.66	-0.735	-1.91	-0.0339
Cardboard	3.46	2.34	5	0.587	0.317	1.21	2.85	1.58	4.41
Steel	5.63	4.59	6.86	4.16	3.3	5.22	1.46	0.00127	2.96
Plastic	6.81	5.62	8.17	7.55	6.29	9.04	-0.722	-2.64	1.16

Figures S1–S5 (below) show Bayesian fits to individual replicate virus decay data for each virus. Replicates are shown in panel columns, viruses in panel rows. Lines are 50 random draws per panel from the posterior

108 distribution of fitted lines, to show level of uncertainty. Time axis is shown out to the latest time taken to
 109 reach an undetectable titer in the considered experimental conditions.



110
 111 Figure S1. Individual replicate fits for aerosols. Columns show replicates, rows show virus (HCoV-19
 112 above, SARS-CoV-1 below). Lines are 50 random draws per panel from the posterior distribution of fitted
 113 lines, to show level of uncertainty.



114
 115 Figure S2. Individual replicate fits for plastic. Columns show replicates, rows show virus (HCoV-19 above,
 116 SARS-CoV-1 below). Lines are 50 random draws per panel from the posterior distribution of fitted lines,
 117 to show level of uncertainty.

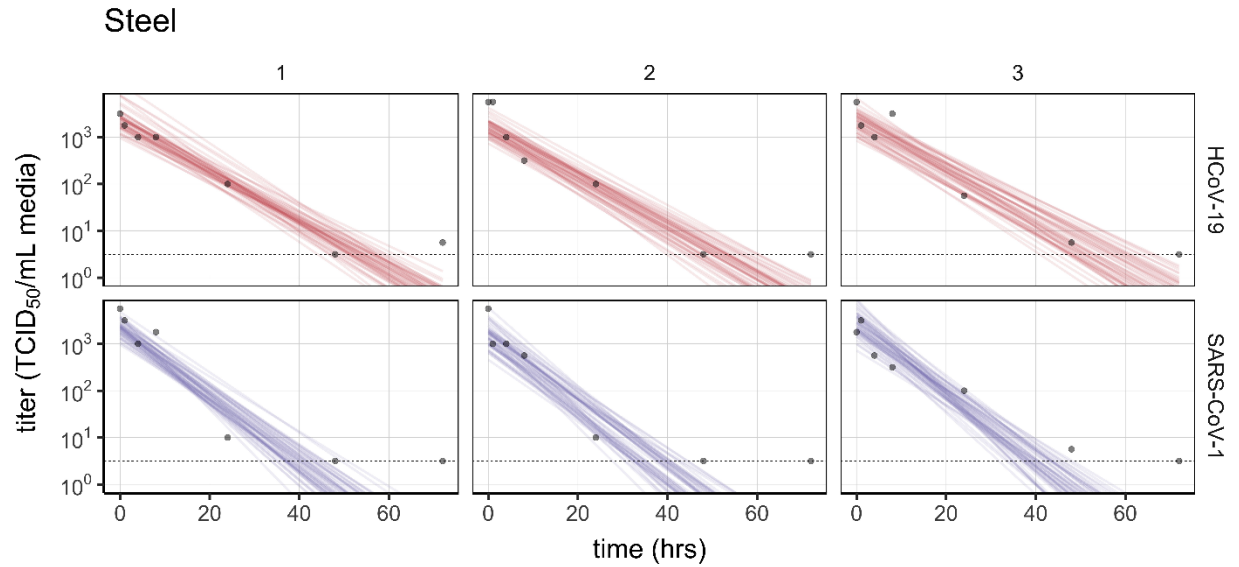


Figure S3. Individual replicate fits for steel. Columns show replicates, rows show virus (HCoV-19 above, SARS-CoV-1 below). Lines are 50 random draws per panel from the posterior distribution of fitted lines, to show level of uncertainty.

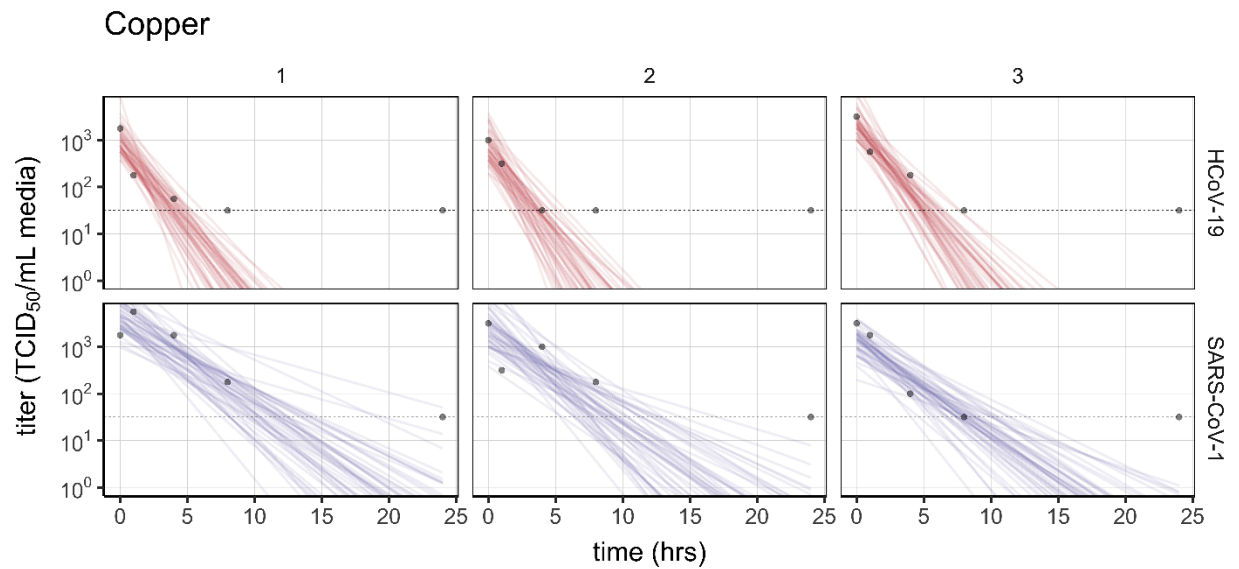


Figure S4. Individual replicate fits for copper. Columns show replicates, rows show virus (HCoV-19 above, SARS-CoV-1 below). Lines are 50 random draws per panel from the posterior distribution of fitted lines, to show level of uncertainty. Fits are substantially poorer for SARS-CoV-1 than for HCoV-19, and data do not follow a linear downward trend over time, suggesting that the difference in observed decay rates should be interpreted with caution.

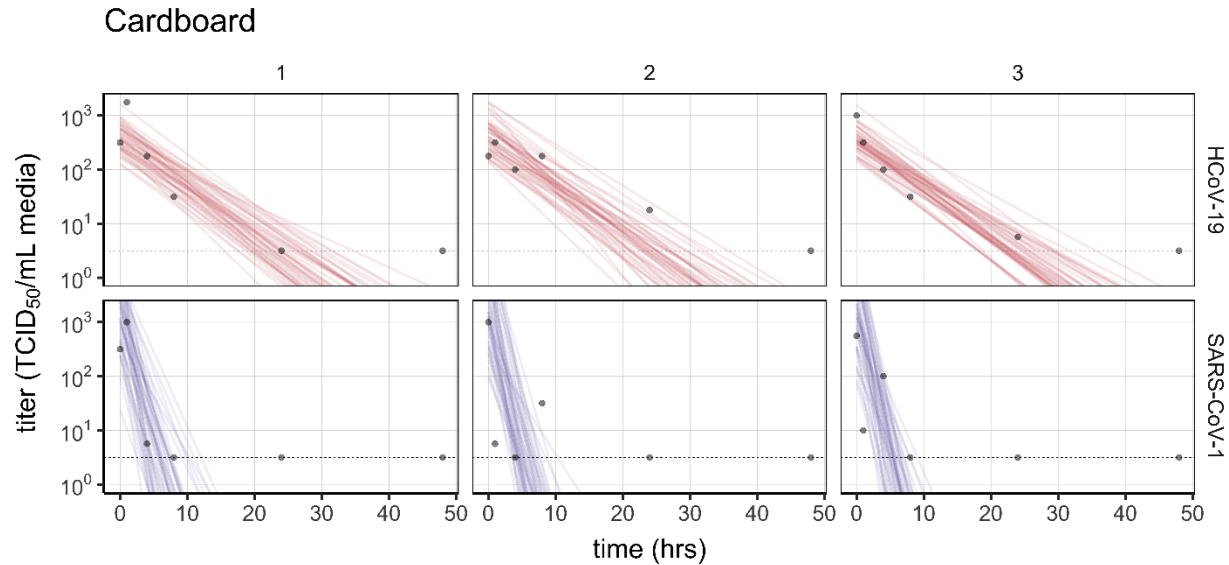


Figure S5. Individual replicate fits for cardboard. Columns show replicates, rows show virus (HCoV-19 above, SARS-CoV-1 below). Lines are 50 random draws per panel from the posterior distribution of fitted lines, to show level of uncertainty. Fits are substantially poorer for SARS-CoV-1 than for HCoV-19, and data do not follow a linear downward trend over time, suggesting that the difference in observed decay rates should be interpreted with caution.

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Code and data availability

Code and data to reproduce the Bayesian estimation results and produce corresponding figures are archived online at OSF: <insert link> and available on Github: <insert link>

Acknowledgements

We would like to thank Kwe Claude Yinde and Michael Letko for experimental assistance. This research was supported by the Intramural Research Program of the National Institute of Allergy and Infectious Diseases (NIAID), National Institutes of Health (NIH). JOL-S and AG were supported by the Defense Advanced Research Projects Agency DARPA PREEMPT # D18AC00031, and JOL-S was supported by the U.S. National Science Foundation (DEB-1557022) and the Strategic Environmental Research and Development Program (SERDP, RC-2635) of the U.S. Department of Defense. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the Centers for Disease Control and Prevention. Names of specific vendors, manufacturers, or products are included for public health and informational purposes; inclusion does not imply endorsement of the vendors, manufacturers, or products by the Centers for Disease Control and Prevention or the US Department of Health and Human Services.