

32 **Abstract**

33 HCoV-19 (SARS-2) has caused >88,000 reported illnesses with a current case-fatality ratio of ~2%. Here,  
34 we investigate the stability of viable HCoV-19 on surfaces and in aerosols in comparison with SARS-  
35 CoV-1. Overall, stability is very similar between HCoV-19 and SARS-CoV-1. We found that viable virus  
36 could be detected in aerosols up to 3 hours post aerosolization, up to 4 hours on copper, up to 24 hours on  
37 cardboard and up to 2-3 days on plastic and stainless steel. HCoV-19 and SARS-CoV-1 exhibited similar  
38 half-lives in aerosols, with median estimates around 2.7 hours. Both viruses show relatively long viability  
39 on stainless steel and polypropylene compared to copper or cardboard: the median half-life estimate for  
40 HCoV-19 is around 13 hours on steel and around 16 hours on polypropylene. Our results indicate that  
41 aerosol and fomite transmission of HCoV-19 is plausible, as the virus can remain viable in aerosols for  
42 multiple hours and on surfaces up to days.

43 A novel human coronavirus, now named severe acute respiratory syndrome coronavirus 2  
44 (SARS-CoV-2, referred to as HCoV-19 throughout this manuscript) emerged in Wuhan, China in late  
45 2019. As of March 3, 2020, >88,000 cases have been diagnosed in 64 countries, including 2915 deaths.<sup>1</sup>  
46 The rapid expansion of this outbreak is indicative of efficient human-to-human transmission.<sup>2,3</sup> HCoV-19  
47 has been detected in upper and lower respiratory tract samples from patients, with high viral loads in  
48 upper respiratory tract samples.<sup>4,5</sup> Therefore, virus transmission via respiratory secretions in the form of  
49 droplets (>5 microns) or aerosols (<5 microns) appears to be likely. Virus stability in air and on surfaces  
50 may directly affect virus transmission, as virus particles need to remain viable long enough after being  
51 expelled from the host to be taken up by a novel host. Airborne transmission or fomite transmission were  
52 thought to play important roles in the epidemiology of the two zoonotic coronaviruses that emerged this  
53 century, SARS-CoV-1 and MERS-CoV.<sup>6</sup> Airborne transmission may have been responsible for the largest  
54 superspreading event during the SARS epidemic of 2002-2003,<sup>7</sup> and numerous nosocomial  
55 superspreading events of SARS-CoV-1 were linked to aerosol-generating medical procedures.<sup>8-10</sup> Fomite  
56 transmission was also suspected during the SARS epidemic, and one analysis of a nosocomial SARS-  
57 CoV-1 superspreading event concluded that fomites had played a significant role.<sup>11</sup>

58 Given the potential impact of different routes of transmission on the epidemiology of emerging  
59 viruses, it is crucial to quantify the virological traits that may shape these aspects of HCoV-19  
60 transmission. Here, we analyze the aerosol and surface stability of HCoV-19 and compare it with SARS-  
61 CoV-1, the most closely related coronavirus known to infect humans.<sup>12</sup> We evaluated the aerosol stability  
62 of HCoV-19 and SARS-CoV-1 for up to three hours in aerosols and up to 7 days on different surfaces.  
63 We estimated decay rates of HCoV-19 and SARS-CoV-1 in each condition using a Bayesian regression  
64 model.

65

## 66 **Methods**

67 HCoV-19 nCoV-WA1-2020 (MN985325.1)<sup>13</sup> and SARS-CoV-1 Tor2 (AY274119.3)<sup>14</sup> were the  
68 strains used in our comparison. Virus stability in aerosols was determined as described previously at 65%

69 relative humidity (RH) and 21-23°C.<sup>15</sup> In short, aerosols (<5 µm) containing HCoV-19 (10<sup>5.25</sup>  
70 TCID<sub>50</sub>/mL) or SARS-CoV-1 (10<sup>6.75-7</sup> TCID<sub>50</sub>/mL) were generated using a 3-jet Collison nebulizer and  
71 fed into a Goldberg drum to create an aerosolized environment. Aerosols were maintained in the  
72 Goldberg drum and samples were collected at 0, 30, 60, 120 and 180 minutes post-aerosolization on a  
73 47mm gelatin filter (Sartorius). Filters were dissolved in 10 mL of DMEM containing 10% FBS. Three  
74 replicate experiments were performed.

75 Surface stability was evaluated on plastic (polypropylene, ePlastics), AISI 304 alloy stainless  
76 steel (Metal Remnants), copper (99.9%) (Metal Remnants) and cardboard (local supplier) representing a  
77 variety of household and hospital situations and was performed as described previously at 40% RH and  
78 21-23°C using an inoculum of 10<sup>5</sup> TCID<sub>50</sub>/mL.<sup>16</sup> This inoculum resulted in cycle-threshold values (Ct)  
79 between 20 and 22 similar to those observed in samples from human upper and lower respiratory tract.<sup>4</sup> In  
80 short, 50 µl of virus was deposited on the surface and recovered at predefined time-points by adding 1 mL  
81 of DMEM. Stability on cardboard was evaluated by depositing 50 µl of virus on the surface and  
82 recovering the inoculum by swabbing of the surface, the swab was deposited 1 mL of DMEM. Three  
83 replicate experiments were performed for each surface. Viable virus in all surface and aerosol samples  
84 was quantified by end-point titration on Vero E6 cells as described previously.<sup>16</sup> The Limit of Detection  
85 (LOD) for the assays was 10<sup>0.5</sup> TCID<sub>50</sub>/mL for plastic, steel and cardboard and 10<sup>1.5</sup> TCID<sub>50</sub>/mL for copper  
86 (due to toxicity caused by the copper in the undiluted samples).

87 The durations of detectability depend on initial inoculum and sampling method, as expected. To  
88 evaluate the inherent stability of the viruses, we estimated the decay rates of viable virus titers using a  
89 Bayesian regression model. This modeling approach allowed us to account for differences in initial  
90 inoculum levels across replicates, as well as interval-censoring of titer data and other sources of  
91 experimental noise. The model yields estimates of posterior distributions of viral decay rates and half-  
92 lives in the various experimental conditions – that is, estimates of the range of plausible values for these  
93 parameters given our data, with an estimate of the overall uncertainty.<sup>17</sup> We describe our modeling  
94 approach in more detail in the Supplemental Materials.

95

## 96 **Results**

97 HCoV-19 remained viable in aerosols throughout the duration of our experiment (180 minutes)  
98 with a reduction in infectious titer 3 hours post-aerosolization from  $10^{3.5}$  to  $10^{2.7}$   $\text{CID}_{50}/\text{L}$  (mean across  
99 three replicates). This reduction in viable virus titer is relatively similar to the reduction observed in  
100 aerosols containing SARS-CoV-1, from  $10^{4.3}$  to  $10^{3.5}$   $\text{TCID}_{50}/\text{mL}$  (mean across three replicates) (Figure  
101 1A).

102 HCoV-19 was most stable on plastic and stainless steel and viable virus could be detected up to  
103 72 hours post application (Figure 1B), though by then the virus titer was greatly reduced (polypropylene  
104 from  $10^{3.7}$  to  $10^{0.6}$   $\text{TCID}_{50}/\text{mL}$  after 72 hours, stainless steel from  $10^{3.7}$  to  $10^{0.6}$   $\text{TCID}_{50}/\text{mL}$  after 48 hours,  
105 mean across three replicates). SARS-CoV-1 had similar stability kinetics and live virus could be detected  
106 on these surfaces up to 72 hours on polypropylene and 48 hours on stainless steel (polypropylene from  
107  $10^{3.4}$  to  $10^{0.7}$   $\text{TCID}_{50}/\text{mL}$  after 72 hours, stainless steel from  $10^{3.6}$  to  $10^{0.6}$   $\text{TCID}_{50}/\text{mL}$  after 48 hours, mean  
108 across three replicates). No viable virus could be measured after 4 hours on copper for HCoV-19 and 8  
109 hours for SARS-CoV-1, or after 24 hours on cardboard for HCoV-19 and 8 hours for SARS-CoV-1  
110 (Figure 1B).

111 Both viruses exhibited exponential decay in viable virus titer across all experimental conditions,  
112 as indicated by linear decrease in the  $\log_{10}\text{TCID}_{50}/\text{mL}$  over time (Figure 2A). From the posterior  
113 distributions on decay slope parameters we computed posterior distributions for the half-life of each virus  
114 in each condition (Figure 2B, Table 1). HCoV-19 and SARS-CoV exhibited similar half-lives in aerosols,  
115 with median estimates around 2.7 hours, and 95% credible intervals (2.5%–97.5% quantile range) of  
116 (1.65, 7.24 hours) for HCoV-19 and (1.81, 5.45 hours) for SARS-CoV-1 (Table 1). Half-lives on copper  
117 were also similar between the two viruses. On cardboard, HCoV-19 showed a considerably longer half-  
118 life than SARS-CoV-1. Both viruses showed markedly longer viability on stainless steel and  
119 polypropylene: the median half-life estimate for HCoV-19 was roughly 13 hours on steel and 16 hours on  
120 polypropylene. In general, there was no statistically discernable difference in half-life between the two

121 viruses on any given surface except for cardboard: all other 95% credible intervals for the difference in  
122 half-lives overlapped 0 (Fig 2B, Table 1).

123

## 124 **Discussion**

125 HCoV-19 has caused many more cases of illness and resulted in more deaths than SARS-CoV-1  
126 and is proving more difficult to contain. Our results indicate that the greater transmissibility observed for  
127 HCoV-19 is unlikely to be due to greater environmental viability of this virus compared to SARS-CoV-1.  
128 Instead, there are a number of potential factors which could account for the epidemiological differences  
129 between the two viruses. There have been early indications that individuals infected with HCoV-19 may  
130 shed and transmit the virus while pre-symptomatic or asymptomatic<sup>4,18-20</sup>. This reduces the efficacy of  
131 quarantine and contact tracing as control measures relative to SARS-CoV-1.<sup>21</sup> Other factors likely to play  
132 a role include the infectious dose required to establish an infection, the stability of virus in mucus, and  
133 environmental factors such as temperature and relative humidity.<sup>16,22</sup> In ongoing experiments, we are  
134 studying virus viability in different matrices, such as nasal secretion, sputum and fecal matter, and while  
135 varying environmental conditions, such as temperature and relative humidity.

136 The epidemiology of SARS-CoV-1 was dominated by nosocomial transmission and SARS-CoV  
137 was detected on variety of surfaces and objects in healthcare settings.<sup>9</sup> HCoV-19 transmission is also  
138 occurring in hospital settings, with over 3000 reported cases of hospital-acquired infections.<sup>23</sup> These cases  
139 highlight the vulnerability of healthcare settings for introduction and spread of HCoV-19.<sup>10</sup> However, in  
140 contrast to SARS-CoV-1, most secondary transmission has been reported outside healthcare settings<sup>23</sup> and  
141 widespread transmission in the community is being seen in several settings, such as households,  
142 workplace and group gatherings.

143 A notable feature of SARS-CoV-1 was super-spreading events, in which a single infected  
144 individual was responsible for a large number of secondary cases, well above the average number denoted  
145 by the reproduction number  $R_{\text{eff}}$ .<sup>7-11,20</sup> A tendency toward such super-spreading events has two important  
146 consequences for the epidemiology of emerging infections: it makes any given introduction of infection

147 more likely to die out by chance, but when outbreaks do occur they are explosive and can overwhelm  
148 hospital and public health capacity.<sup>24</sup> A number of hypothesized super-spreading events have been  
149 reported for HCoV-19. Given that SARS-CoV-1 superspreading events were linked to aerosol and fomite  
150 transmission,<sup>6-11</sup> our finding that HCoV-19 has viability in the environment comparable to that of SARS-  
151 CoV-1 lends credence to the hypothesis that it too may be associated with superspreading.

152 We found that the half-life of HCoV-19 on cardboard is longer than the half-life of SARS-CoV-1.  
153 It should be noted that individual replicate data were noticeably noisier for this surface than the other  
154 surfaces tested (Figures S1–S5), so we advise caution in interpreting this result.

155 Here, we show that the stability of HCoV-19 and SARS-CoV-1 under the experimental  
156 circumstances tested is similar. Taken together, our results indicate that aerosol and fomite transmission  
157 of HCoV-19 are plausible, as the virus can remain viable in aerosols for multiple hours and on surfaces up  
158 to days.

159

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173 **Code and data availability**

174 Code and data to reproduce the Bayesian estimation results and produce corresponding figures are

175 archived online at OSF: <insert link> and available on Github: <insert link>

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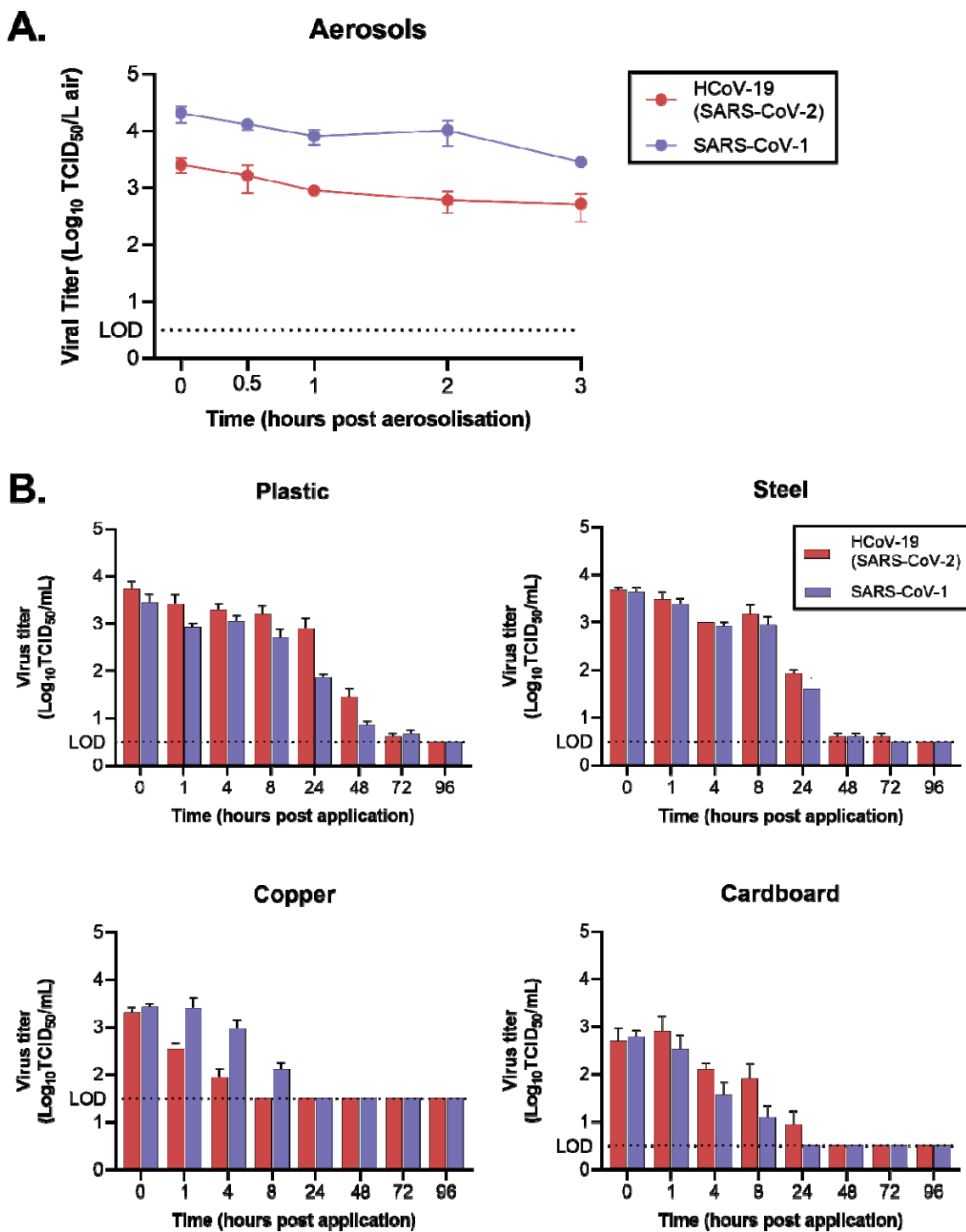
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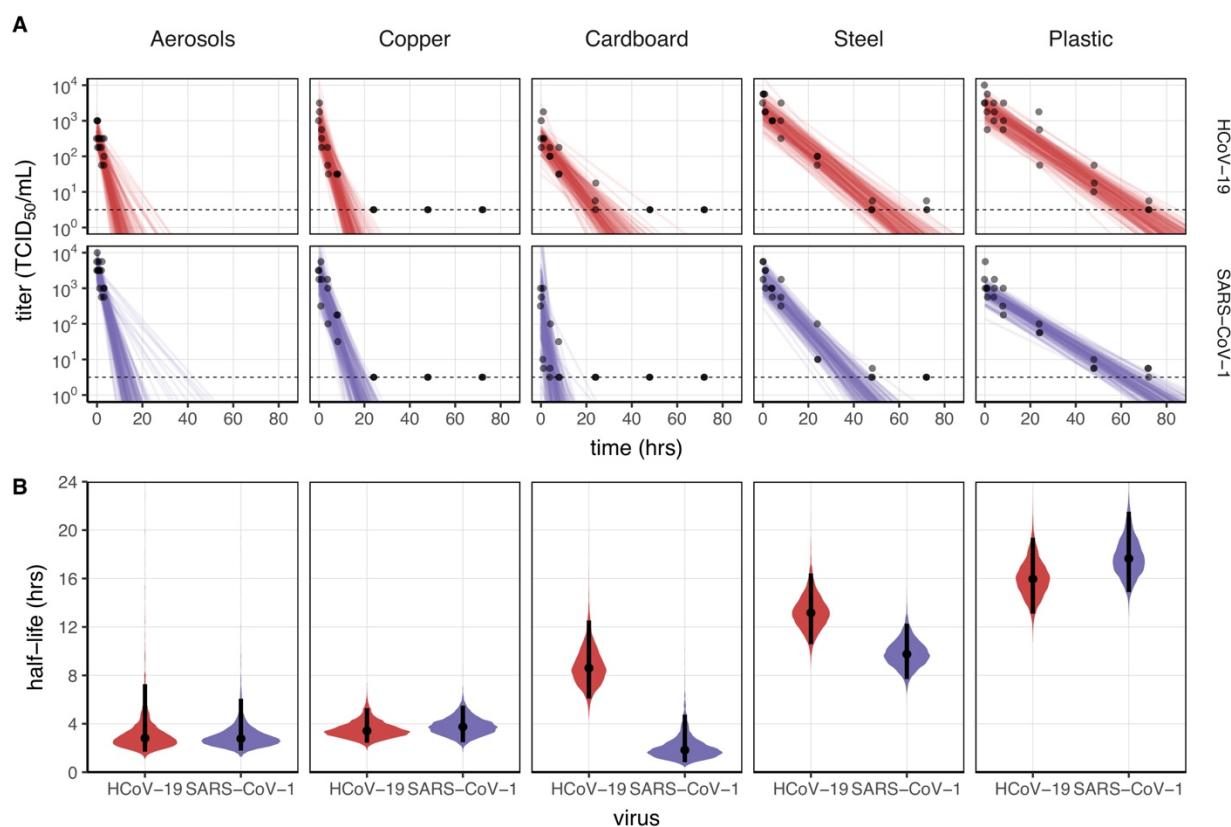
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 230 Figure 1. Viability of SARS-CoV and HCoV-19 in aerosols and on different surfaces. A) SARS-CoV and  
 231 HCoV-19 were aerosolized in a rotating drum maintained at 21-23°C and 65% RH. Aerosols were

232 maintained over 180 minutes and samples were collected at 0-, 30-, 60-, 120- and 180-minutes post  
233 aerosolization. Viable virus titer per liter of air is shown in TCID<sub>50</sub>/L air. B) 50  $\mu$ l of 10<sup>5</sup> TCID<sub>50</sub>/mL of  
234 SARS-CoV and HCoV-19 was applied on plastic, steel, copper and cardboard surfaces. At 1, 4, 8, 24, 48,  
235 72, and 96 hours samples were obtained for viability assessment. All samples were quantified by end-  
236 point titration on Vero E6 cells. Plots show the mean and standard error across three replicates. Dotted  
237 line shows Limit of Detection (LOD), 10<sup>0.5</sup> TCID<sub>50</sub>/mL for plastic, steel and cardboard and 10<sup>1.5</sup>  
238 TCID<sub>50</sub>/mL for copper.



239  
240 Figure 2. Estimated exponential decay rates and corresponding half-lives for HCoV-19 and SARS-CoV-  
241 1. Experimental conditions are ordered by posterior median half-life for HCoV-19. A: Regression plots  
242 showing predicted decay of virus titer over time; titer plotted on a logarithmic scale. Points show  
243 measured titers and are slightly jittered along the time axis to avoid overplotting. Lines are random draws  
244 from the joint posterior distribution of the exponential decay rate (negative of the slope) and intercept  
245 (initial virus titer), thus visualizing the range of possible decay patterns for each experimental condition.

246 150 lines per panel: 50 lines from each plotted replicate. Dotted line shows Limit of Detection (LOD),

247  $10^{0.5}$  TCID<sub>50</sub>/mL. B: Violin plots showing posterior distribution for half-life of viable virus. Dot shows

248 the posterior median estimate and black line shows a 95% credible interval.

249

250 Table 1. Posterior median estimates and 95% credible intervals (2.5%–97.5% quantile range) for half-

251 lives of HCoV-19 and SARS-CoV in aerosols and on various surfaces, as well as a median estimate and

252 95% credible interval for the difference between the two half-lives (HCoV-19 – SARS-CoV).

253

<i>Material</i>	<b>HCoV-19</b>			<b>SARS-CoV-1</b>			<b>HCoV-19 – SARS-CoV-1</b>		
	<i>median</i>	2.5%	97.5%	<i>median</i>	2.5%	97.5%	<i>median</i>	2.5%	97.5%
Aerosols	2.74	1.65	7.24	2.74	1.81	5.45	-0.00418	-2.72	4.45
Copper	3.4	2.4	5.11	3.76	2.43	5.43	-0.321	-2.31	1.78
Cardboard	8.45	5.95	12.4	1.74	0.827	4.42	6.6	3.07	10.7
Steel	13.1	10.5	16.1	9.77	7.69	12.3	3.36	-0.173	7.12
Plastic	15.9	13	19.2	17.7	14.8	21.5	-1.79	-6.31	2.51

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- 5

6                   **Aerosol and surface stability of HCoV-19 (SARS-CoV-2) compared to SARS-CoV-1**

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