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Review article

SARS-CoV-2 viability under different meteorological conditions, surfaces, fluids and transmission between animals

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ABSTRACT

Since the COVID-19 outbreak, researchers have tried to characterise the novel coronavirus SARS-CoV-2 to better understand the pathogenic mechanisms of the virus and prevent further dissemination. As a consequence, there has been a bloom in scientific research papers focused on the behaviour of the virus in different environmental contexts. Nevertheless, despite these efforts and due to its novelty, available information about this coronavirus is limited, as several research studies are still ongoing. This review aims to shed light on this issue. To that end, we have examined the scientific literature to date regarding the viability of SARS-CoV-2 on surfaces and fluids or under different environmental conditions (temperature, precipitation and UV radiation). We have also addressed the role of animals in the transmission of this coronavirus.

1. Introduction

During the first months of SARS-CoV-2 outbreak in Wuhan (Hubei Province, China) in 2020–the epidemiological epicenter of COVID-19–some investigations already warned of a possible global pandemic as a consequence of a low control of people's mobility from the focus of contagion to other countries (Khan et al., 2020a, 2020b, 2020c). Despite the lockdown of Wuhan aimed to avoid higher infection cases, lack of knowledge regarding the virus viability and dissemination mechanisms ultimately triggered the fear of disease, promoting not only physical damage but also mental health problems (Khan et al., 2020b).

This work has been carried out in the midst of the global COVID-19 pandemic, a disease that represents a new challenge, as little is understood about its etiology and there is still no treatment or vaccine that have proven effective against SARS-CoV-2 infection. Moreover, the literature regarding the behaviour of this coronavirus on different surfaces, fluids or under the influence of different environmental factors is scarce. And there is also great uncertainty concerning the role that animals may play as possible vectors of contagion.

Due to the novelty of the disease, it is important to highlight the scope and limitations of the conclusions that can currently be drawn from the literature. The great global impact of this disease has enabled the implementation of numerous studies in which different organizations, universities and even countries are now contributing. However, due to this exceptional and urgent situation, many consulted papers are still not peer-reviewed. Some of the results presented on those studies must be corroborated with further research and some could be complemented with available information regarding related coronaviruses to cover the knowledge deficiencies on SARS-CoV-2. As a result, keeping updated is proving challenging because these large studies being carried out are mixed with papers done in a more local context, and the information is sometimes unreliable.

It is therefore necessary to be critical with all the information published by unreliable sources. Hence, this work attempts to be an exhaustive and critical review regarding the existing information of the survival of SARS-CoV-2 under different conditions. For this reason, we supply a complete review of the elements that are decisive to the expansion and control of the COVID-19 pandemic, providing actual data.

For ease of reference, this document has been divided into three

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parts. The first part that talks about concrete virus viability on different surfaces, as well as fluids such water and air. The second part focuses on the virus viability under varied environmental conditions that traditionally modify the expansion capacity of viruses, such as temperature, UV radiation, humidity, and precipitation. Finally, the last part aims at the possible role animals may play as vectors for the virus.

2. Material and methods

This study has involved the analysis of official databases, such as PUBMED database (https://pubmed.ncbi.nlm.nih.gov/), as well as the Web of science of the Spanish Foundation for Science and Technology (FECYT, https://www.recursoscientificos.fecyt.es/). Only papers that have passed a peer review system have been considered. The bibliographic review has included research published until June 29, 2020.

We must point out that, given the heterogeneity of results between studies, the precautionary principle was chosen and the intervals that point to a longer virus survival presence of the virus in time were chosen. In this way, the conclusions are drawn within safety margins.

It should also be noted that the terminology used in scientific publications varies between survival, presence, viability, stability and persistence. Only the term viability has been used in this work to denote the retention of the infective capacity of the virus. It should be noted that this viability is determined in cell cultures, not in animal or human tests. Finally, it is important to note that viability is not an absolute value, but rather a time range determined by specific environmental conditions.

3. Results and discussion

3.1. SARS-CoV-2 viability on surfaces and fluids

3.1.1. Surfaces

When this report was being written, the World Health Organization (WHO) established that there was still not enough scientific evidence regarding the viability of SARS-CoV-2 on inert surfaces and common fluids such as water. The WHO refers to published data on the feasibility of MERS-CoV and SARS-CoV-1. Consulted literature lists the viability of the virus on different surfaces.

Scientific reports dealing with the viability of the virus on surfaces affirm that the virus can stay for a variable period on different surfaces (Kampf et al., 2020) maintaining its infective potential (Table 1). However, the fact that the virus is present on a surface does not mean that the surface itself is infective. That is to say, SARS-CoV-2 infects mainly through the respiratory tract. Therefore, touching a contaminated surface does not imply infection unless the contact with the surface ends up into mucous membranes (which is indeed a potential source of infection).

3.1.2. Air

Studies published to date regarding SARS-CoV-2 survival in the air and aerosols are based on a methodology hardly exportable to standard conditions. Despite this, two conclusions can be drawn from these studies: 1) SARS-CoV-2 can be detected in air samples in spaces with a continuous infection source (mainly hospital rooms or elevators); 2) SARS-CoV-2 is also detectable in poorly ventilated or crowded spaces.

There is some controversy regarding the air's capability of transporting and maintaining the virus. The studies carried out by van Doremalen and collaborators indicate that the virus is viable at least for 3 h in an artificially generated aerosol (van Doremalen et al., 2020). Nevertheless, SARS-CoV-2 viability in aerosols was assessed in experimental conditions (65–100%relative humidity (RH)), which are far from the actual conditions in hospital rooms (RH ~ 30%) or outdoor spaces. This fact led to criticism (Rubens et al., 2020; Leshe et al., 2020; Helmers et al., 2020; Petti et al., 2020; Schwartz et al., 2020; Judson et al., 2020). However, a recent review work published by Jayaweeraa and colleagues compiles evidence showing SARS-COV-2 transmission through virus-laden droplets and aerosol. The authors analyze the airborne virus transmission in different spaces and highlight the importance of wearing facial masks to reduce the infectious risk (Jayaweeraa et al., 2020).

Ong et al. did not find presence of the virus in air samples belonging to the room of three symptomatic COVID-19 patients (Ong et al., 2020). It is noteworthy that all samples (door handle, toilet bowl, table …) collected from one of these patients' rooms were positive. Samples from furniture of the other two patients' rooms were collected after routine cleaning and consequently tested negative. This fact emphasizes the importance of a correct disinfection of surfaces and its impact in potential infections.

Scientists from Wuhan found positive air samples from two hospitals in the Chinese city and its surrounding area (Liu et al., 2020). Nevertheless, it is worth mentioning that some samples revealed a very low concentration, close to the limit of detection. Those tested as positive outside hospitals came from areas with a high confluence of people (eg. supermarket entrances). The presence of SARS-CoV-2 in aerosol drops of different sizes (Lesho, 2020) suggests these drops may originate from multiple sources, as sneezing, coughing, talking or from the movement or evaporation of infected surfaces. Interestingly, the virus can be transmitted through the air to far-off places (>10 m). Setti and collaborators demonstrated the presence of SARS-CoV-2 in particulate matter in North Italy. This may have promoted the high infection and disease severity rates in this Italian area. Besides, dust storms may also spread the virus to distant zones, as demonstrated for the influenza virus (aL. Setti et al., 2020a, 2020b). Air pollution is known to be responsible for prolonged inflammation, eventually leading to an innate immune system hyper-activation and it also affects the defensive efficacy of the cilia present in the upper airways. Therefore, a person living in a highly polluted area is more susceptible to develop chronic respiratory diseases. This would explain the increased fatality rate of COVID-19 in North Italy compared to other Italian regions (Conticini et al., 2020).

3.1.3. Water

There is no evidence that human coronavirus has transmitted through contaminated drinking water (Naddeo and Liu, 2020). In general, enveloped viruses are more sensitive to oxidants such as chlorine (Eslami and Jalili, 2020; Wang et al., 2005a, 2005b). SARS-CoV-2 is likely to inactivate more quickly than non pathogenic intestinal human viruses transmitted through water in contact with oxidizing agents (La Rosa, Bonadonna et al., 2020). Temperature is a key factor that influences the virus viability as the virus title diminishes more rapidly at 23 °C – 25 °C than at 4 °C (La Rosa et al., 2020a). The SARS coronavirus has been detected in wastewater but not as infectious particles. There is no current evidence that human coronaviruses are present in surface or groundwater or are transmitted through contaminated drinking water (La Rosa et al., 2020a). More research is needed to adapt the commonly used methods for sampling and concentration measurement of non-enveloped virus to enveloped virus (La Rosa et al., 2020a, 2020b).

Some effective methods to detect enveloped virus, and particularly coronavirus, in water are recommended (Caducci et al., 2020):

- To assess the survival of these viruses in natural conditions, in different types of water and at different temperatures.
- To evaluate the efficiency of water treatments and disinfection in order to avoid the contamination of both urban and hospital sewage.
- To analyze the implications for the reuse of water for agriculture considering the possibility that it ends up deposited in food (raw vegetables) and pollution.
- To establish a system to monitor sewage to assess the possible circulation of the virus.

3.1.4. Disinfection techniques for hospital wastewater

The similarities between SARS-CoV-1 and SARS-CoV-2 lead us to believe that SARS-CoV-2 may also be sensitive to the same environmental factors and disinfectants. Therefore, similar disinfection

Table 1
Survival of SARS-CoV-2 and other related coronaviruses on different surfaces and aerosols.

Surface	Virus	Strain	Dose	Cells	Temp. (°C)	RH (%)	Survival period	Reference
Stainless Steel	MERS-CoV	hCoV-EMC 2012	1E+05	Vero E6	20	40%	2 days	van Doremalen et al. (2013)
			1E+05	Vero E6	30	30%	8–24 h	van Doremalen et al. (2013)
			1E+05	Vero E6	40	80%		van Doremalen et al. (2013)
	HCoV	strain 229E	1E+03		21		5 days	Warnes et al. (2015)
	SARS-CoV-2	nCoV-WA1-2020		Vero E6			3 days	van Doremalen et al. (2020)
Copper	SARS-CoV-2	nCoV-WA1-2020		Vero E6			4 h	van Doremalen et al. (2020)
Aluminum	HCoV	strain 229E y OC43	5E+03		21		2–8 h	Sizun et al. (2000)
Metal	SARS-CoV-1	strain P9	1E+05		25 (RT)		5 days	Duan et al. (2003)
Wood	SARS-CoV-1	strain P9	1E+05		25 (RT)		4 days	Duan et al. (2003)
Paper	SARS-CoV-1	strain P9	1E+05		25 (RT)		4–5 days	Duan et al. (2003)
		strain GVU6109	1E+06		25 (RT)		24 h	Duan et al. (2003)
			1E+05		25 (RT)		3 h	Duan et al. (2003)
			1E+04		25 (RT)		>5 min	Lai et al. (2005)
Cardboard	SARS-CoV-2	nCoV-WA1-2020					1 day	van Doremalen et al. (2020)
Glass	SARS-CoV-1	strain P9	1E+05		25 (Rt)		4 days	Duan et al. (2003)
	HCoV	strain 229E	1E+03		21		5 days	Warnes et al. (2015)
Plastic	SARS-CoV-1	strain KHU39849	1E+05		22–25		5 days or less	Chan et al. (2011)
		strain P9	1E+05		25 (RT)		4 days	Duan et al. (2003)
		strain FFM1	1E+07		25 (RT)		6–9 days	Rabenau et al. (2005)
	HCoV	strain 229E	1E+07		25 (RT)		2–6 days	Rabenau et al. (2005)
	MERS-CoV	HCoV-EMC 2012	1E+05		20		2 days	van Doremalen et al. (2013)
			1E+05		30		8–24 h	van Doremalen et al. (2013)
	SARS-CoV-2	nCoV-WA1-2020		Vero E6			3 days	van Doremalen et al. (2020)
PVC	HCoV	Strain 229E	1E+03		21		5 days	Warnes et al. (2015)
Silicon rubber	HCoV	Strain 229E	1E+03		21		5 days	Warnes et al. (2015)
Sterile latex	HCoV	Strain 229E and OC43	5E+03		21		<8 h	Sizun et al. (2000)
Disposable gown	SARS-CoV-1	strain GVU6109	1E+06		25 (RT)		2 days	Lai et al. (2005)
			1E+05		25 (RT)		1 day	Lai et al. (2005)
			1E+04		25 (RT)		1 h	Lai et al. (2005)
Cotton gown	SARS-CoV-1	GvU6109	1E+06		20 (RT)		24 h	Lai et al. (2005)
			1E+05		20 (RT)		1 h	Lai et al. (2005)
			1E+04		20 (RT)		5 min	Lai et al. (2005)
Ceramic tiles	HCoV	Strain 229E	1E+03		21		5 days	Warnes et al. (2015)
Teflon	HCoVstrain 229E		1E+03		21		5 days	Warnes et al. (2015)
Aerosol	SARS-CoV-2	nCoV-WA1-2020		Vero E6			>3 h	van Doremalen et al. (2020)
Tap water	HCoV	Strain 229E		ATCC-740	23 °C		12,1 days	Gundy et al. (2009)
					4 °C		Estimated 588 days	Gundy et al. (2009)
	FIPV			ATCC-990	23 °C		12,5 days	Gundy et al. (2009)
					4 °C		Estimated 130 days	Gundy et al. (2009)
	PV1				23 °C		Estimated 71,3 days	Gundy et al. (2009)
					4 °C		Estimated 203 days	Gundy et al. (2009)
	SARS-CoV-1				20 °C		2 days	Wang et al. (2005)
					4 °C		>14 days	Wang et al. (2005)
Primary effluent wastewater[a]	HCoV	Strain 229E		ATCC-740	23 °C		3,54 days	Gundy et al. (2009)
	FIPV			ATCC-990	23 °C		2,56 days	Gundy et al. (2009)
	PV1				23 °C		10,9 days	Gundy et al. (2009)
	MHV				25 °C		13 days	Ye et al. (2016)
	MHV				10 °C		36 days	Ye et al. (2016)
	SARS-CoV-1	BJ0			20 °C		2 days	Wang et al. (2005)
		BJ0			4 °C		>14 days	Wang et al. (2005)
	SARS-CoV-2				RT		Positive detection	Medema et al. (2020) Wu et al. (2020) Ahmed et al. (2020) La Rosa et al. (2020)
Secondary effluent wastewater[a]	HCoV	Strain229E		ATCC-740	23 °C		2,77 days	Gundy et al. (2009)

(continued on next page)

Table 1 (*continued*)

Surface	Virus	Strain	Dose	Cells	Temp. (°C)	RH (%)	Survival period	Reference
	FIPV			ATCC-990	23 °C		2,42 days	Gundy et al. (2009)
	PV1				23 °C		5,74 days	Gundy et al. (2009)
Lake water	TGEV				25 °C		13 days	Casanova et al. (2009)
	MHV				25 °C		10 days	Casanova et al. (2009)
Urine	SARS-CoV-1	BJ0			20 °C		>17 days	Wang et al. (2005)
Stool	SARS-CoV-1	BJ0			20 °C		3 days	Wang et al. (2005)
Food	Mers-CoV				4 °C		72 h	Carratuno et al. (2020)
Lettuce	HCov	Strain 229E					4 days	Carraturo et al. (2020)

TEMP: temperature; RH: relativa huminidy; RT: Room temperature..

[a] *Primary effluent was collected after settling and secondary effluent was collected prior to chlorination.*

technologies are applied to hospital waste and sewage. SARS-CoV-1 could exist for 2 days, 3 days, and 17 days in hospital wastewater, faeces, and urine at 20 °C, respectively (Wang et al., 2005a). All SARS viruses could be inactivated within 30 min at 20 °C with more than 0.5 mg/L residual free chlorine or 2.19 mg/L residual chlorine dioxide remaining (Chen et al., 2006) and by comparing the performance of disinfection of different technologies irradiation with chlorine and UV were the most efficient, followed by chlorine dioxide, and disinfection with ozone was the worst (Wang et al., 2020).

Disinfection with chlorine (liquid chlorine, chlorine dioxide and sodium hypochlorite) is adopted, traditionally used in the disinfection of sewage in hospitals in China, with a solution of approximately 50 mg/L. For the disinfection of the septic tank, the duration contact should be greater than 1.5 h with residual chlorine greater than 6.5 mg/L and fecal coliform colonies less than 100 per liter. In addition, UV radiation and heating are also recommended for wastewater disinfection in other COVID-19 designated hospitals due to the lower amount of by-products and ideal disinfection performance. The water quality of the wastewater discharged from the hospital must meet several requirements explained in Wang et al. (2020). They explain the maximum of 900 MPN/L fecal coliforms, the absence of enteric pathogens and *Mycobacterium tuberculosis*, a minimum time of 1,5 h and 0,5 h with disinfectant chlorination or Chlorine dioxide respectively and residual chlorine test of ⩾6.5 for chlorination or ⩾4 for Chlorine dioxide method.

With respect to the waste in hospitals, the complete incineration of the waste, a Ph of more than 12 after 24 h of disinfection, and >200 mg/L of chlorine residue.

In addition, infectious waste should also be disinfected with disinfectants containing solid or liquid chlorine with an available chlorine concentration of 20 g/L and a disinfection duration of 2 h, and it is advisable to incinerate pharmaceutical and chemical waste. It is suggested that radioactive waste contaminated with SARS-CoV-2 be disinfected as infectious waste after storing it for at least 10 half-lives. Disposable protective products should also be treated as infectious waste. For example, respirators should be soaked in 75% alcohol for 30 min. In addition, chlorine disinfectants with 500 mg/L and 1000 mg/L are recommended for disinfection of other protective products without or with obvious contamination, respectively. It is crucial to develop strategies to minimize the environmental pollution caused by this practice, being conscious of its effects (Nabi et al., 2020a, 2020b; Nabi and Khan, 2020). Other recommendations to follow regarding the disinfection of hospital waste are:

- o Hospital waste and sewage and the use of wells/seepage wells to discharge sewage and sludge, or discharge into the sanitary protection zone of drinking water sources, should also be strictly prohibited.
- o Hospitals must establish a recycling and management system, assign specific personnel in charge, and strengthen management in each department to avoid waste loss.
- o Personnel involved in the disposal of disposable medical supplies must be qualified and their personal protection reinforced.

There are also other more advanced technologies for treating wastewater and hospital waste, such as radiation disinfection technology, reverse polymerization disinfection technology, plasma disinfection technology, and thermal gasification disinfection technology, which are always recommended when they are implemented at the hospital, but due to high investment costs, these technologies have not been used on a large scale (Wang et al., 2020).

3.2. Viability of SARS-CoV-2 in different weather conditions

Weather conditions seem to influence the expansion of COVID-19 (Byass, 2020), although the authors do not agree on defining this influence. The findings regarding the different parameters are summarized below.

3.2.1. Temperature

There is great uncertainty about the influence of higher temperatures in the expansion of COVID-19. The urgency to publish may have compromised the quality of data collected, as different studies report issues when comparing countries at the same epidemiological moment.

There is an inverse correlation between the average temperature of a

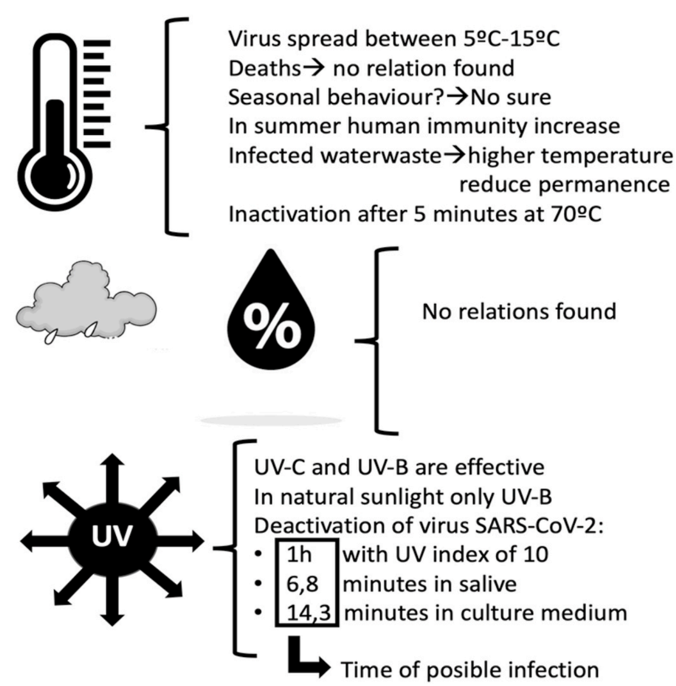

Fig. 1. Relation between atmospheric parameters and COVID-19 spread.

country and the transmission of COVID-19 (Falcão et al., 2020; Lin et al., 2020) (Fig. 1). An increase of one degree Fahrenheit in the mean temperature would suppose a reduction of 1.44–6.4 cases/day depending on the model used. However, these same authors defend that there is no correlation between the number of deaths by COVID-19 and the average temperature of the countries when studying a global database (Falcão et al., 2020). Although there is a study that does find a significant correlation between mortality and temperature drop, it is restricted to data collected in China (Ma et al., 2020), so the results shall not be extrapolated.

Xie and Zhu (2020) indicate that there is no demonstrable relationship between COVID-19 expansion and temperature in ranges above 3 °C and a positive linear correlation below. To conclude this, 122 cities in China were analyzed.

There are studies that found that 60.0% of the 3,750,000 confirmed cases of COVID-19 studied in 185 countries or regions from January 21 to May 6, 2020, occurred in places where the air temperature ranged from 5 °C to 15 °C, with a peak in cases at 11.54 °C. The pandemic has not spread due to high population density, but appears to follow a curve that will continuously move to higher latitudes throughout the temperature zone between 5 °C and 15 °C over time. Therefore, they predict that the scale of the COVID-19 pandemic could recur in large mid-latitude cities by fall 2020 (Huang et al., 2020).

Another study comprising 33 Chinese locations from January 29 to February 15 already indicated that COVID-19 was more infective in areas with temperatures between 10 °C and 20 °C, and with ranges of relative humidities between 10% ≤ RH b 20% (Xu et al., 2020).

Winter is the peak season in the northern hemisphere for the four seasonal human coronaviruses: HKU1, NL63, OC43, and 229E (hereafter collectively referred to as "seasonal CoVs") (Al-Khannaq et al., 2016; Friedman et al., 2018; Galanti et al., 2019; Góes et al., 2019; Huang et al., 2017; Killerby et al., 2018). These viruses cause respiratory infections that are generally mild and primarily affect young children, for example, the 2009 H1N1 pandemic virus (A/H1N1pdm09) which originated in March 2009 in Mexico and spread worldwide in a matter of weeks. The virus showed a low prevalence during summer and pronounced peaks in the following autumn and winter in many countries (Amato-Gauci et al., 2011) and the A/H1N1pdm09 virus has subsequently gone on to show a seasonal pattern causing winter epidemics in temperate climates. Seasonal CoVs show strong and consistent seasonal variation, and the modeling suggests that this requires strong variability in transmissibility throughout the year. Despite the current spread of COVID-19 throughout the ecuador and the tropics have been significantly lower (Kumar et al., 2020a), it should be noted that SARS-CoV-2 appears to be transmitted in tropical climates such as Singapore, so winter is not a necessary condition for the spread of SARS-CoV-2 (Neher et al., 2020) and seasonality alone is unlikely to end with the spread of SARS-CoV-2 as seen across asian countries. There is no evidence to support that COVID-19 case counts decrease in warmer weather, providing useful implications for policy makers and the public (Xie and Zhu, 2020). A spatio-temporal analysis of the early evolution of COVID-19 across the provinces of Spain –which presented significant differences in temperature during March 2020– has revealed no consistent evidence of a correlation between temperature variation and COVID-19 spread rates (Briz-Redón and Serrano Arouca, 2020).

There are scientific studies that indicate that human immunity increases during summer due to favorable seasonal variation in genetic activities, blood composition and adipose tissue (Kumar et al., 2020a). However, factors such as the prevalence of carriers, the efficacy of the treatment of the sewage load (virus source) and the level of expansion will continue to be critical variables.

Temperature can impact the permanence of COVID-19 in wastewater, because the arrival of warm weather and the increase in wastewater temperatures in the northern hemisphere could result in a lower prevalence of COVID-19 in some communities (Hart and Halden, 2020). Therefore, there is a need to establish enhanced sewage surveillance (Nabi et al., 2020).

In any case, It was found that the use of heat is a valid method to inactivate the virus in a solution, with 5 min at 70 °C and is also the most scalable and easiest to use viral disinfection method (Liao et al., 2020). The virus is highly stable at 4 °C, but sensitive to heat. At 4 °C, there was only a 0.7 log reduction in infectious titer on day 14. With the incubation temperature increased to 70 °C, the time for virus inactivation was reduced to 5 min (Chin et al., 2020).

Heat (≤85 °C) under various humidity conditions (≤100% relative humidity, RH) was found to be the most promising, non-destructive method for protecting the filtering properties of "meltblown" fabric as well as N95-grade respirators. At 85 °C, 30% RH, it was possible to carry out 50 cycles of heat treatment without significant changes in filtration efficiency. With low humidity or dry conditions, and temperatures up to 100 °C, no significant alterations in filtration efficiency were found after 20 treatment cycles (Liao et al., 2020). Indeed, the inactivation of other coronavirus was more rapid at 40 degress than at 20 degrees, and higher at 20 degrees than at 4 degrees C at all humidity levels, but working better under low humidity (Casanova et al., 2010).

3.2.2. Precipitation, relative humidity, cloud cover and pressure

Some authors found a positive correlation between precipitation and SARS-CoV-2 infections spread (Falcão et al., 2020). However, relative humidity was not considered in the study, which could have interfered with the results. Conversely, this study found no relationship between precipitation and COVID-19 deaths. This was corroborated by another report (Gunthe et al., 2020) which found that precipitation, relative humidity, and cloud cover are unrelated to the virus spread (Gunthe et al., 2020; Kumar et al., 2020b; Rendana, 2020). Nevertheless, there is another study which defends that high relative humidity promotes COVID-19 transmission when temperature is low, but tends to reduce transmission when temperature is high (Lin et al., 2020). However, those people physiologically adapted to live in a hypoxic environment due to high altitudes appear to be protected from the severe impact of acute infection with the SARS-CoV-2 virus (Arias-Reyes et al., 2020).

3.3. Ultraviolet radiation

There is still few evidence that UV light may be effective for inactivating SARS-CoV-2 (Leund and Tak Chueng, 2020). However, some studies demonstrate an effective inactivation with germicidal UV of other beta-coronaviruses structurally similar to SARS-CoV-2 (such as SARS-CoV-1 and MERS-CoV).

The International Lighting Commission subdivides the UV spectrum into three bands based on wavelength, and UV-C radiation has the shorter wavelength (from 100 to 280 nm) and the most energetic one. This makes UV-C the most effective tool for both viral sterilization and air and surfaces disinfection. Germicidal ultraviolet radiation (GUV) and UV germicidal radiation (UVGI) are based on UV-C radiation (Houser, 2020), which damages the SARS-CoV-2 RNA, avoiding virus replication. v Exposure to sunlight does not contain UV-C but contains UV-B, which has lower effectivity, so may not prove a reliable method to inactivate SARS-CoV-2 as the amount of UV radiation varies with time of the day, season, weather and latitude. After 1 h of sunlight with an UV index of 10, 99.9% on a surface can be inactivated (Houser, 2020). However, solar radiation does not prevent the virus from spreading in densely populated areas (Guasp et al., 2020), and direct sunlight radiation is also harmful to human skin and eyes (Leund and Tak Chueng, 2020; Houser, 2020). UV-A are not appreciably harmful to people or the SARS-CoV-2 virus.

Other experiments performed by simulating sunlight from the summer solstice (at 40° N latitude, at sea level, on a clear day) indicated that 90% of the virus was inactivated after 6.8 min in simulated saliva and after 14.3 min in culture medium. There was also significant inactivation, albeit at a slower rate, under lower levels of simulated sunlight. The most effective ultraviolet range was UV-B (280–400 nm), constant across different levels of UV-A and UV-B irradiance averaged $3.2 \times 10^{-3} \pm 7.5 \times 10^{-5}$ W/m^2 (Ratnesar-Shumate et al., 2020).

For viruses suspended in simulated saliva, the inactivation rates from exposure to any level of UV-B irradiation was significantly faster than that observed in the dark. Furthermore, the inactivation rates observed for UV-B irradiations of 1.6 y 0.7 W/m^2, corresponding to the period of March–June, were significantly higher than those observed for 0.3 W/m^2 (December–February) (Ratnesar-Shumate et al., 2020). This study provides the first evidence that sunlight can rapidly inactivate SARS-CoV-2 on surfaces, suggesting that surface, viability, and risk of exposure can vary significantly between indoor and outdoor environments. However, to fully assess the risk of exposure in outdoor environments, we should also include information about the viral load present on surfaces, the efficiency of virus transfer from those surfaces to contact, and the amount of virus required to cause infection.

Although there is no evidence of a decrease in COVID-19 cases due to increased UV index, it is remarkable that the number of accumulated cases was higher for countries with a UV index. 2.5 and gradually decreased from a UV index of 3.5 (Gunthe et al., 2020).

There is an agreement that the use of UV is a valid procedure to sterilize (Liao et al., 2020) but it degrades the materials (for example, respirators degraded after 20 UV sterilization cycles). And in addition, its use must be regulated and training required, since several families were harmed while trying this method for disinfecting their homes (Leund and Tak Chueng, 2020). Phototoxicity due to the misuse of UV germicidal lamps for domestic disinfection causes ophthalmological and skin damage if not used properly.

Viral inactivation of UV-C radiation can be considered in steps. The first step represents 90% inactivation, the second step, 99% inactivation, and the third step, 99.9% inactivation, and so on. Reduction at each step requires a doubling of the UV-C radiation dose to achieve the same degree of viral inactivation –if the intensity is doubled, the exposure time can be cut in half-. Quantitatively, dose (μJ/cm^2) = UV-C fluence (μW/cm^2) × duration of exposure (s).

LED emitters that produce UV-C radiation are not easily found. Most commercially available UV LEDs emit longer wavelength UV, which is less effective for virus inactivation. A low pressure mercury discharge emits a significant fraction of its radiation at 253.7 nm, so low pressure mercury lamps are by far the most common type of UV-C source.

In healthcare settings, airborne UV-C radiation systems should be expected to be at least partially effective in reducing viral transmission. In these systems, a fixture containing a source that generates UV-C radiation is mounted above head height and UV-C radiation is directed into the upper air of the room. UV-C should always be used in unoccupied spaces. It may also be used at heights that are out of reach and out of sight to decrease the spread of COVID-19 by inactivating the SARS-CoV-2 virus in air and on surfaces, including sterilization of personal protective equipment. It should not be used in residential environments (Houser, 2020) or to disinfect hands or other parts of the body.

3.4. SARS-CoV-2 transmission between animals

It is yet poorly understood how animals have transmitted SARS-CoV-2 to human beings, and much remains to be elucidated regarding which species may act as natural reservoirs or transmission vectors for the virus.

3.4.1. Are domestic animals/pets transmission vectors?

According to the available literature, pets are regarded as collateral victims of the COVID-19 pandemic and not as transmission vectors for the virus. Cats, dogs and ferrets are susceptible to infection by nasal inoculation of large viral dosages (conditions different to those at the domestic environment) (Shi et al., 2020; Schlottau et al., 2020). However, these species are not equally affected. The virus replication rate is low in dogs, while in both cats and ferrets, the virus shows a greater replication rate and possible –although ineffective– transmission to other animals of the same species. The performed experiments also showed that pigs, ducks and chicken are not susceptible to SARS-CoV-2 infection. Other studies report ferrets are susceptible to SARS-CoV-2 infection and within-species transmission (Kim et al., 2020; Richard et al., 2020).

Several cats and dogs have tested positive for SARS-CoV-2, although none has presented symptoms nor died as a result of COVID-19 (Leroy et al., 2020). A positive 17-year-old dog died in Hong Kong apparently due to heart and kidney failure. In Spain, a SARS-CoV-2 positive cat that presented cardiomyopathy was euthanized and the autopsy revealed no COVID-19-related lesions (Sáez, 2020). Furthermore, two farms in the Netherlands reported infections in minks, which presented respiratory symptoms and lung damage upon necropsy (Oreshkova et al., 2020). In all reported cases, pet owners had previously presented COVID-19 symptoms. Therefore, it was concluded that animals were infected by their owners. Moreover, the infected animals did not present a high viral load and were not considered infectious (Leroy et al., 2020). However, there is still an ongoing investigation regarding a possible mink to human infection in the mink farms.

3.4.2. Research models and possible natural reservoirs

Aside from the reported infections in domestic animals, SARS-CoV-2 was detected in several tigers and lions from a New York zoo. These animals developed mild respiratory symptoms after being infected, most likely by a caretaker (Hosie et al., 2020). This shows that SARS-CoV-2 can infect wild species apart from domestic animals. The identification of these species may help determine which are more suitable as COVID-19 research models for studying the disease and for testing candidate treatments and vaccines.

Mice are not susceptible to SARS-CoV-2 infection and are, therefore, not suitable as research models (Zhou et al., 2020). An alternative would encompass the use of transgenic mice that express human ACE2 (Bao et al., 2020; Winkler et al., 2020), the protein that mediates coronavirus entry in the cells. Another approach consists in modifying the S protein of SARS-CoV-2 so it can infect mouse cells via mouse ACE2 (Dinnon et al., 2020). Conversely, some studies propose the use of golden hamsters (Chan et al., 2020; Imai et al., 2020), ferrets (Kim et al., 2020; Richard et al., 2020) and macaques (Shan et al., 2020; Yu et al., 2020; Rockx et al., 2020). This is supported by experiments that prove these species can be infected by SARS-CoV-2, develop COVID-19-like tissue alterations and produce antibodies against the virus. Furthermore, ferrets and hamsters have been reported to infect individuals of the same species both by air and direct contact.

The identification of host species for SARS-CoV-2 is also crucial for determining which are the natural reservoirs for coronavirus. This could help prevent new outbreaks and contribute to protecting the balance in ecosystems, as some species may be particularly vulnerable to pneumonia viral infections (Nabi et al., 2020a,b). In this regard, multiple *in silico* studies computationally predict whether SARS-CoV-2 can bind with the ACE2 protein of different species. Some of these studies analyze the amino acid sequence of the receptor (Liu et al., 2020; Luan et al., 2020a; Qiu et al., 2020), while others research the interaction between the virus with the receptor (Luan et al., 2020b). Collectively, these investigations predict the interaction of SARS-CoV-2 with the ACE2 from apes, Old World monkeys, ruminants, pigs, rabbits, dogs, felins, hamsters and cetaceans. Concurrently, the same studies dismiss any possible infections in rodents (mice, rats, guinea pigs), New World monkeys, marsupials, monotremes, birds, reptiles, amphibians and fish. Nevertheless, opposite conclusions are obtained regarding species as bats, pangolins, snakes and tortoises, so caution is advised while interpreting these results. Moreover, *in silico* studies should be experimentally confirmed. In this sense, different *in vitro* studies prove SARS-CoV-2 can efficiently bind to the ACE2 protein from multiple pets (cat, dog, rabbit), cattle (horse, goat, sheep, cow, pig) and wild animals as macaque, horseshoe bat, civet or pangolin (Zhou et al., 2020; Zhao et al., 2020). These reports also conclude that the virus cannot efficiently bind to the receptor of rodents (mouse, rat, guinea pig), New World monkeys or birds (chicken).

Collectively, many efforts are aimed towards identifying which species are susceptible to SARS-CoV-2 infection and could act as viral reservoirs, transmission vectors or research models. However, many studies are yet to be validated *in vivo* before drawing definitive and solid conclusions.

4. Conclusions

SARS-CoV-2 can persist differently according to the surface, from hours to days (SARS-CoV-2 viability varies from hours to days depending on the surface), but infection only occurs when touching mucus membranes after contact with these contaminated surfaces. SARS-CoV-2 can also persist in air droplets for an uncertain period of time that could be longer if the virus is attached to pollution particles. Wastewater and tap water could act as SARS-CoV-2 propagation tools since positive samples of SARS-CoV-2 have been found in water samples in different countries worldwide.

In terms of SARS-CoV-2 behavior facing environmental conditions, this novel coronavirus differs from other members of its family. SARS-CoV-2 has been detected in high temperature areas, meanwhile other coronaviruses' presence is reduced in similar conditions. Hence, is not possible to confirm that high temperature avoids further transmission of the virus. Additionally, temperatures oscillating between 5 °C and 15 °C could be beneficial for viral spread. However, no significant correlation between mortality and local temperature has been identified yet.

Precipitation, relative humidity, and cloud cover are not related to the virus spread, and people physiologically adapted to living in hypoxic environments seem to be more protected against SARS-CoV-2 severe infection.

An UV (UV–B or UV-C) index of 10 could achieve the inactivation of the virus within 1 h or 6.8 min in simulated saliva, although further research in this field is required. Sunlight disinfectant effectiveness is higher in low population locations.

In relation with the role of animals in the spread of COVID-19, experimental studies have shown that cat, dogs, and ferrets are susceptible to SARS-CoV-2 infection. Despite the concern for the back-to-human infection from minks, pets (cat and dogs) and farm animals (such as poultry or pigs) are not likely to directly transmit the virus to humans, and they would be rather acting as a fomites. Meanwhile, infected humans carrying SARS-CoV-2 virus could be responsible for the infection in some animals. As a research tool, conventional rodent models are not useful for the study of COVID-19 since they cannot be infected by the virus. Alternative models such a transgenic mice, hamsters, ferrets or macaques should be used instead. Also, computational studies indicate a possible interaction of the virus with some mammals, such as apes and ruminants, but these studies should be validated *in vivo*.

Credit author statement

María Fernández-Raga: Methodology, Writing - original draft preparation-Supervision; Laura Díaz-Marugán: Methodology, Writing - original draft; Marta García: Writing - original draft and Writing-Reviewing; Carlos Bort: Conceptualization; Víctor Fanjul: Supervision and Writing-Reviewing.

Declaration of competing interest

The Authors of declares that there is no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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