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# Study on the decay characteristics and transmission risk of respiratory viruses on the surface of objects

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## ABSTRACT

The complex and changeable environment is a brand-new living condition for the viruses and pathogens released by the infected people to the indoor air or deposited on the surface of objects, which is an important external condition affecting the decay and transmission risk of the viruses. Exposure to contaminated surfaces is one of the main routes of respiratory diseases transmission. Therefore, it is very important for epidemic prevention and control to study the law of virus decay and the environmental coupling effect on various surfaces. Based on the analysis of the influencing mechanism, a large amount of experimental evidence on the survival of viruses on the surface of objects were excavated in this paper, and the effects of various factors, such as surface peripheral temperature, relative humidity, virus-containing droplet volume, surface materials and virus types, on the decay rate constants of viruses were comprehensively analyzed. It was found that although the experimental methods, virus types and experimental conditions varied widely in different experiments, the virus concentrations on the surface of objects all followed the exponential decay law, and the coupling effect of various factors was reflected in the decay rate constant  $k$ . Under different experimental conditions,  $k$  values ranged from 0.001 to 100 h<sup>-1</sup>, with a difference of 5 orders of magnitude, corresponding to the characteristic time  $t_{99}$  between 500 and 0.1 h when the virus concentration decreased by 99%. This indicates a large variation in the risk of virus transmission in different scenarios. By revealing the common law and individuality of the virus decay on the surface of objects, the essential relationship between the experimental observation phenomenon and virus decay was analyzed. This paper points out the huge difference in virus transmission risk on the surface at different time nodes, and discusses the prevention and control strategies to grasp the main contradictions in the different situations.

## 1. Introduction

In recent times, the novel coronavirus (SARS-CoV) (Zhong et al., 2003), H1N1 influenza virus (Morris, 2010), Middle East respiratory syndrome coronavirus (MERS-CoV) (Zaki et al., 2012; de Wit et al., 2016), and the emerged Novel Coronavirus (SARS-CoV-2) (Zhang et al., 2020a) have caused worldwide pandemics. These viruses cause a serious threat to human life (Song et al., 2019) and the pandemic has a lasting and certainly negative impact on our lives (Khurshheed et al., 2020).

Three possible routes of transmission of infectious respiratory infections are currently known: aerosol transmission, short-range droplet transmission and contact with contaminated surfaces (Xiao et al., 2018).

Studies have shown that contact with contaminated surfaces is a predominant transmission route for some respiratory diseases (Kampf et al., 2020; Otter et al., 2016). Due to the diversity of cultural backgrounds and customs of social groups, people have not yet adopted good hygiene habits. When coughing or sneezing, they do not pay attention to covering their mouths and noses and consequently spray out a large number of virus-containing droplets, which are the potential carriers of pathogens (Morawska and Cao, 2020). The droplets rapidly settle or splash down on the surface of objects and cause pollution. Researchers have shown that some viruses can last on different surfaces from hours to a few days (Marquès and Domingo, 2021). During this period people may have contact with the surfaces of contaminated objects in social life,

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however, when exposed to an environment with potential viruses or in contact with contaminated objects, they can't wash and disinfect their hands in time, or unconsciously touch their mouth, nose, eyes, etc., which may cause personal infection. During disease transmission, the infectious droplet particle size varies widely, and the transmission risk varies significantly at different time nodes (Mao et al., 2020). Furthermore, the complex and changeable external environment is a brand-new living condition for the viruses and pathogens released by the infected people to the indoor air or deposited on the surface of objects, which is an important external condition affecting the decay and transmission risk of the viruses. Therefore, the transmission risk of contaminated surfaces should not be ignored, and it is very important to study the decay of viruses on the surface of objects and the influence of the related factors on epidemic prevention and control.

A great deal of work has been done in the qualitative study of the decay characteristic of pathogens on the surface of objects. The survival of viruses on a surface is affected by many factors such as virus type, surface characteristics, droplet volume, environmental temperature and humidity. Noti et al. (2013) showed that when the ambient temperature was 20 °C, the number of infectious H1N1 influenza viruses was significantly lower than 20% at the relative humidity of 45%. Marr et al. (2019) found that temperature and relative humidity would affect the stability of the viruses, in which relative humidity determined the evaporation rate of the virus-containing droplets. Evaporation would then affect the size, physical fate and chemical microenvironment of the droplet, which in turn would affect the chemical microenvironment of the viruses, and determine the survival of the viruses. Kumar et al. (2020a) discussed that the increase of temperature and biological activities may reduce the prevalence of COVID-19, and SARS-CoV-2 is likely to have less endurance at high temperature and humidity. Kumar et al. (2020b) found that susceptibility and inactivation led to seasonal epidemics of SARS-COV-2, meaning that temperature had an important influence on virus inactivation. In addition, some scholars have linked nanoscience and virology to provide a smart molecular diagnosis/-treatment for pandemic viral infections (Mukherjee et al., 2020). Furthermore, Thomas et al. (2008) assessed the survival of human influenza viruses on banknotes, and pointed out that the concentration of viruses should be high enough to cause infection. Therefore, the number of virus-containing droplets deposited on the surface also plays a decisive role in the transmission risk of contaminated surfaces. In addition, different surface material properties also can affect the virus decay on the surface. For example, influenza viruses survived a much shorter time on copper than on stainless steel (Noyce et al., 2007). However, there are quite different views on the persistence of viruses on the surface of objects. Some scholars believe that human coronaviruses and influenza viruses, including MERS, have a limited capacity to survive on dry surfaces (Kramer et al., 2006; Geller et al., 2012; Yezli and Otter, 2011). The results of sampling from different places in the hospital ward and on the surfaces of objects contacted by patients showed that the number of infectious SARS-CoV-2 viruses ranged from several to dozens of copies/mL (Ong et al., 2020; Razzini et al., 2020; Peyrony et al., 2020), which was much lower than the virus concentration of  $10^3$ - $10^8$  copies/mL in nasal swabs and throat swabs of infected patients (Pan et al., 2020). It seems that the viruses have limited viability on the surface. However, a few studies suggested that viruses such as SARS-CoV, MERS-CoV and the influenza virus had the capacity to survive on dry surfaces for a sufficient duration (Chan et al., 2011; Coulliette et al., 2013; van Doremalen et al., 2013). Bilal et al. (2020) indicated that the survival time of the viruses on various inanimate surfaces depends on the environmental and growth conditions, and that the overall survival rate can range from a few minutes to a month. Therefore, the risk of transmission by contaminated surfaces should be taken seriously.

In terms of quantitative study of the virus decay characteristic on the surface of objects, most of the related literatures used survival time to describe the speed of virus decay. Van Doremalen et al. (van Doremalen

et al., 2020) studied the change of virus concentration of SARS-COV-2 over time on copper, cardboard, stainless steel and plastic surfaces, and found that the half-life of virus (the time for virus concentration to decrease by 50%) was significantly different on each surface. The half-life of virus was relatively small on copper and cardboard, 1.5 h and 0.587 h respectively. On stainless steel and plastic surfaces, the time was longer, 4.16 h and 7.55 h respectively. Warnes et al. (2015) titrated a suspension of human coronavirus 229 E on the surface of copper, and the results showed that the inactivation rate of the viruses was approximately 8 times faster when titrated with 1  $\mu$ L inoculum than 20  $\mu$ L. Kumar et al. (2021) used the polyethylene glycol (PEG) method and found that the RNA abundance of SARS-COV-2 was reduced  $>1.3 \log_{10}$  during Upflow Anaerobic Sludge Blanket (UASB) treatment. However, there were relatively few researches on the decay rate constant. In 1948, Dunklin (Dunklin and Puck, 1948) first proposed the law that viruses and other microorganisms decay with a natural index over time after leaving the host. Later, few scholars fitted the decay constant according to experimental test data (Zhao et al., 2012; Silverman and Boehm, 2020). Chin et al. (2020) carried out experiments on the SARS-CoV-2 virus on surfaces such as glass, and found that the virus decay was divided into two stages. In the first 3 h, the virus decay rate constant was large, while in the later period, the decay rate constant was quite small.

To sum up, although the existing literature reports qualitative and quantitative studies on the effects of various factors on the virus decay on the surface of objects, there is still a lack of systematic research. Because different scholars may have different experimental methods, detection methods and experimental environments, the scattered results may lead to uncertainty in the horizontal comparison of experimental results, and the information conveyed may be biased. In particular, the volume of the virus suspension titrated on the surface varies greatly. Moreover, in order to emphasize the risk of transmission, scholars often focused on describing how long the viruses survived or whether they remained active. The risk level of virus infection on the surface at different time nodes has been downplayed and the disunity of information has caused public panic. Some research results may be misinterpreted for the epidemic prevention and control departments and public administration. Then departments may introduce intervention policies that fail to address the main contradiction, and they may be too aggressive in dealing with the dying viruses and not enough in dealing with the real enemy (the viruses with high initial concentration and vigorous vitality), thus, the opportunity of prevention and control could be missed. Therefore, sound science is essential to decision-making in response to current and future public health pandemics (Zhang et al., 2020b). All these problems highlight the necessity of systematically developing the law of virus decay on the surface of objects. Therefore, based on the analysis of the influence mechanism of virus survival, our study analyzes the changes of the concentration and infectious of the viruses and their viral surrogates on the surface of the objects over time by digging out a large amount of experimental evidence in the existing literature, and we calculate the decay rate constants of viruses under various experimental conditions. The macroscopic environment, the number of viruses deposited on the object, the surface materials, the types of viruses and other factors affecting the law of virus decay on the surface and the difference of transmission risk are analyzed comprehensively.

## 2. Mechanism analysis and methodology

Respiratory virus is a kind of acellular organism, which must be parasitized in living cells and proliferates by replication. When it is released from patients through breathing, talking, coughing, or sneezing, it floats in the air or settles to the surface of various objects (as shown in Fig. 1). The viruses on the contaminated surface can be transferred to the hands and continuously transferred from contaminated hands to more surfaces. Touching the mouth, nose and eyes with contaminated hands may cause the viruses to re-enter susceptible

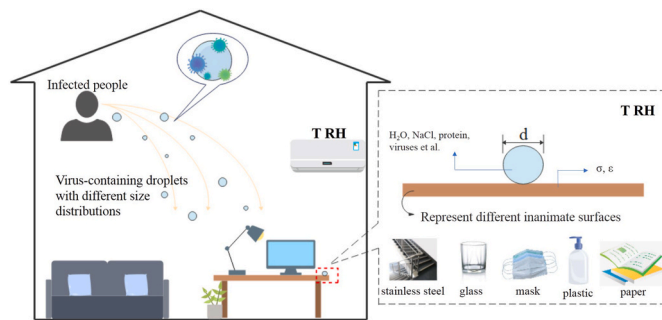


Fig. 1. Influencing factors of virus survival on the surface of objects and virus transmission.

individuals, thereby causing the disease to spread. When the viruses are in the human body, due to the moderate temperature, sufficient moisture, rich nutrition, salt and acid-base balance, it is in a suitable condition for survival and replication. Once leaving the host, the large-size droplets float in the air and settle on the surface of objects, where the living environment changes suddenly and the viruses became less active or even inactivated with the passage of time. A large number of studies have shown that for many microorganisms, including respiratory pathogens, once they leave their original environment, the change of the relative survival rate  $C/C_0$  over time usually follows an exponential function (Dunklin and Puck, 1948):

$$\frac{C}{C_0} = e^{-kt} \quad (1)$$

where  $C$  is the virus concentration at time  $t$ ,  $TCID_{50}/mL$ ;  $C_0$  is the initial virus concentration,  $TCID_{50}/mL$ , which generally refers to the initial sampling concentration after the virus is titrated to the surface;  $T$  is the duration of virus deposition on the surface,  $h$ ;  $k$  is called the virus decay rate constant on the surface of objects,  $h^{-1}$ , and its numerical value reflects how quickly the viruses in the suspension decay on the surface of the new environment.

From equation (1), the scientific description of the law of decay after the viruses are released from an infected individual to the surface is very concise, and the complex effects of various factors are concentrated in the decay rate constant, which is difficult to be analyzed by the physical and mathematical models at present. In the medical field, experimental methods are often used to simulate the deposition of viruses on different surfaces to obtain the decay rate constants. In the laboratory, a certain concentration of a virus suspension is prepared, and a certain volume of droplets is titrated on the surface of various objects. Under the controllable laboratory environment conditions, a virus-containing droplet (residue) is sampled at different time points, and the virus concentration at different time points is obtained by the plaque method or the PCR technique. Then, according to equation (1), the experimental data are collated to obtain the decay rate constants of different viruses under various conditions. Although scholars in the medical field have carried out a lot of original work on related aspects, the detection methods might be different in the experimental processes, and the temperature and humidity conditions in various experimental environments are quite different. Therefore, it is impossible to make a horizontal comparison between the curve of virus decay over time, and there is still a lack of systematic research on the influencing mechanism. Considering that, based on the existing experiments, this paper intends to reveal the correlation between various factors and the virus decay rate constants on the surface of objects through mechanism analysis, and reveal the influencing laws of different factors from the macro perspective.

The first step is to clarify the relationship between virus decay on the surface of objects and the risk of transmission. The viruses on the surface do not exist alone, especially in the medical experiments where the volume of the titrated virus-containing droplets is large and may contain

a large number of viruses (the droplets exhaled by an infected individual are similar), so the experimental results have statistical significance. Only by correlating the relative survival rate with the absolute virus concentration can the risk of transmission be revealed. Secondly, the possible influence of various factors on the virus decay on the surface should be clarified. Fig. 1 shows the factors that influence virus decay. Equation (2) can be used to qualitatively describe the influence of various factors on the virus decay rate constant:

$$k = f(\text{virus}, V, d, \sigma, \epsilon, T, RH, \dots) \quad (2)$$

where *virus* represents different kinds of respiratory viruses;  $V$  represents the total volume of virus-containing droplet settled or titrated to the surface,  $\mu L$ ;  $d$  is the particle size of a single droplet settled on the surface,  $\mu m$ ;  $\epsilon$  is the porosity of the object surface, %, reflecting the surface material and water absorption degree;  $\sigma$  is the surface tension,  $N/m$ , reflecting the aggregation state of droplet on the surface;  $T$  is the ambient temperature around the surface;  $RH$  is the relative humidity of the environment.

Obviously, there are significant differences in the microstructure of viruses due to different types of viruses. Once the environment changes, the damage to the structure is also different, and there may be differences in the laws of decay. The difference in droplet volume or diameter greatly affects the speed of water evaporation and the increasing rate of the concentration of each component under specific temperature and humidity conditions, which directly affects the speed of the virus decay process. The differences in material, porosity, surface tension and water absorption characteristics of the objects will also directly affect the morphology and physical change process of the virus-containing droplets on the surface. The experimental temperature and relative humidity around the surface are the boundary constraints of the physical processes such as heat and mass transfer, evaporation and concentration. Finally, the coupling effect of various factors determines the value of the decay rate constants under different experimental conditions. In order to find out the influence of various factors on the decay of virus through medical experiments, we searched the research studies on virus decay on the surface of different objects. Twelve publications, a total of 96 experiments, were selected in which we could calculate the virus decay rate constant  $k$  on the surface of objects in order to study the decay law of respiratory viruses on the surface.

Due to the complexity of the problem, the existing medical experiments on virus survival are relatively scattered. It is very difficult to find a single factor for the virus decay rate constants. By viewing the existing literature, the research results of virus survival on the surface of objects were usually given in terms of the time required for virus decay to a certain concentration or the curve of virus concentration changing with time. Therefore, in this paper, the decay rate constants of viruses on the surface of objects in experiments in the relevant literature are calculated by two methods. On the one hand, if the experimental results give the time required for the virus concentration to drop to 90% or 99% of the initial concentration, that is  $t_{90}$ ,  $t_{99}$ , or the time required for the virus to decay to other degrees of inactivation (such as half-life  $t_{50}$ , etc.), the virus decay rate constant  $k$  can be calculated according to the proportion of the virus concentration to the initial concentration and the corresponding time required. For example, in one experiment, the time when the virus concentration drops to 90% of the initial concentration,  $t_{90}$ , is 2 h, and at this time  $C/C_0 = 0.1$ , the decay rate constant  $k$  of the virus on the surface of objects under the experimental condition can be calculated as 1.15. On the other hand, if the researcher only gives the curve of virus concentration change over time or the curve of virus relative survival rate change over time, the data sequence of the virus concentration measured at each time node in the figure within the publication can be obtained by using GetData software. According to equation (1),  $\ln \frac{C}{C_0} = -kt$  can be obtained, that is,  $\ln (C/C_0)$  has a linear relationship with time  $t$ . Then the virus decay rate constant  $k$  ( $h^{-1}$ ) can be calculated as the regression slope of  $\ln (C/C_0)$  versus time (in hours) using linear



least squares regression. In this formulation,  $C$  is the virus concentration at time  $t$ , and  $C_0$  is the initial virus concentration at the beginning of the experiment (i.e.,  $t = 0$ ). When using a graph to show the influence of a single factor on the decay rate constant  $k$ , since  $k$  in different experimental conditions differed by several orders of magnitude, the  $k$  values were  $\log_{10}$ -transformed ( $\log_{10}k$ ) according to the practice in the medical literature. In this way, readers can make a more intuitive comparison of the decay rate constant  $k$ , which has orders of magnitude differences. Therefore, in the analysis of the influence of various factors on the virus decay on the surface of objects,  $\log_{10}k$  was used to reflect the decay rate constant in the ordinate of the graph.

Since the ultimate goal of this study is to reveal the decay law of viruses on the surface of objects and provide a reference for epidemic prevention and control, we analyze the essence of virus decay and experimental observations in the discussion section. The relationship between the decay rate constants and half-life,  $t_{90}$ ,  $t_{99}$  or other indicators is discussed, and the main contradiction between the transmission risk of contaminated surfaces and disease control analyzed. This is the focus of this article.

It should be noted that, considering the safety of the experimental process with highly infectious human respiratory viruses, many researchers choose closely related viral surrogates, including the murine hepatitis virus (MHV), transmissible gastrointestinal virus (TGEV) and other animal viruses, as well as phage phi 6 and MS2, etc. Therefore, these virus surrogates are also included in this study to compare and analyze the decay characteristics of viruses on the surface of objects under various factors.

### 3. Results

Our research found that in different experimental conditions the types of viruses or surrogates (14 types), the surface types (41 types), and the volume of the titration droplet (1.0–500  $\mu\text{L}$ , 6 levels, individual unreported) were different, especially the temperature and relative humidity of the experimental environment were quite different. Some experiments gave specific values, while some gave ranges, and some did not even mention them. This has made it difficult for us to extract the influence of a single factor on the virus decay rate constants under the same or similar conditions through the limited experimental research results. Nevertheless, in order to take this meaningful and complex problem a step forward, and being scientific and rigorous, we still present the existing results with the influence of a single factor on the virus decay rate constants on the surface of objects, and reveal the common laws under complex coupling conditions.

#### 3.1. The effect of temperature on surface survival

The survival of viruses on the surface of objects over time at different temperatures has been examined in a relatively large number of studies. Fig. 2 shows the logarithmic variation of the decay rate constant of respiratory viruses on surfaces with the change of temperature according to 47 sets of experiments conducted by 7 scholars (van Doremalen et al., 2020; Warnes et al., 2015; Chin et al., 2020; Casanova et al., 2010; Bearden and Casanova, 2016; Sizun et al., 2000; Kratzel et al., 2020). It was found that the experiments conducted by different scholars on the influence of temperature on the survival of the viruses on the surface of objects focused on several limited working conditions of low temperature 4 °C, laboratory temperature 20–25 °C and high temperature 40 °C, and experimental data for other temperatures were lacking. On the whole, in the temperature range from 4 °C to 40 °C, the viruses had smaller decay rate constants on the surface of objects and could remain active for a longer time; as the temperature rose, the decay rate constants gradually increased, and the viruses remained active on the surface for a shorter time, and the risk of transmission decreased. It indicated that the lower the temperature was, the more conducive it would be to the survival of the viruses on the surface, while the higher

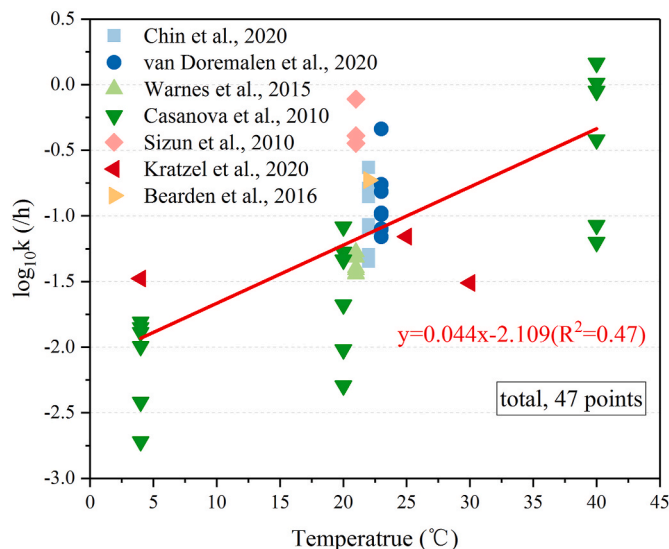


Fig. 2. Variation of virus decay constant with temperature.

the temperature was, the risk of virus transmission would be suppressed, showing obvious common characteristics. In addition, it should be noted that even under the same temperature conditions, there was a significant difference in the decay rate constants of the viruses on the surface, up to two orders of magnitude or more, which was the result of the coupling effects of different experimental conditions. The red solid line in the figure is the fitting curve of the virus decay constants and temperature. The statistical outcome was that the logarithm of the virus decay rate constants on the surface of objects increased by about 0.22 for every 5 °C increase in the environmental temperature. To a certain extent, it can be quantified that an appropriate increase in the environmental temperature was conducive to the inhibition of disease transmission. Chin et al. (2020) tested the stability of SARS-COV-2 on a culture medium surface at different temperatures. The results showed that the virus was highly stable at 4 °C, while the temperature was increased to 70 °C, the viruses were inactivated within 5 min, proving that temperature had an important influence on the decay of the virus.

#### 3.2. The effect of relative humidity on surface survival

Patients exhaled virus-containing droplets float through the air and then settle on the surface of objects. The relative humidity around the surface influences the evaporation rate of the droplets and the physical process of changes in the concentration of compounds such as salt and protein in the droplets, thus affecting the survival of the viruses. Fig. 3 shows the logarithm of the decay rate constants of respiratory viruses on

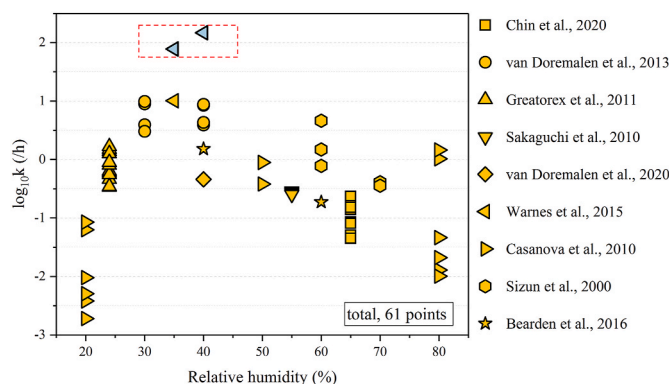


Fig. 3. Changes of virus decay rate constants with relative humidity.

the surface with the change of relative humidity in 61 sets of experimental results obtained from 9 studies (van Doremalen et al., 2013, 2020; Warnes et al., 2015; Chin et al., 2020; Casanova et al., 2010; Bearden and Casanova, 2016; Sizun et al., 2000; Sakaguchi et al., 2010; Greatorex et al., 2011). It can be seen that with regard to relative humidity more experiments have been carried out on virus decay, and experimental data are available at representative nodes in the RH range of 20–80%. In general, viruses in a relatively dry or humid environment have a lower decay rate constant, while viruses in a moderate relative humidity environment (30–60% RH) have a higher decay rate constant, showing an “inverted U-shaped” distribution pattern. It should be noted that, even under the same relative humidity, there are significant differences in the decay rate constant of the viruses. The difference in  $k$  values can be up to two orders of magnitude, especially in dry or humid environments. This is the result of different coupling effects of other experimental conditions. The larger the decay rate constant, the lower the survival rate of the viruses on the surface. Fig. 3 also confirms that the relevant experimental results showing that the influence of relative humidity on the relative survival rate of the viruses is roughly U-shaped (Lin and Marr, 2019; Yang et al., 2012; Prussin et al., 2018). In particular, the virus decay rate constants  $\log_{10}k$  (marked with blue dots in the figure) in the experimental conditions in the range of 30–40% relative humidity in Fig. 3 were as high as 2. This is due to the titration volume of the virus suspension in the two experiments being only 1  $\mu\text{L}$ , which led to faster virus inactivation. The mechanism that affects the persistence of the viruses on the surface is explained later. More importantly, the above-mentioned influence of the temperature and relative humidity of the space environment on the virus decay rate constants on the surface of objects has important implications for scientific and reasonable indoor environmental regulations to reduce the risk of transmission.

### 3.3. The effect of droplet volume on surface survival

The volume of the titrated virus suspension has the least changes in the existing experimental literature. Generally, there are 5–6 titration volumes, and most experiments use a titration volume of 10  $\mu\text{L}$ . Fig. 4 shows the logarithmic decay rate constants of respiratory viruses on the surface change with the titrated droplet volume. The  $k$  values were obtained from the results of 35 sets of experiments in 9 articles under basically similar laboratory temperature environments (van Doremalen et al., 2013, 2020; Warnes et al., 2015; Chin et al., 2020; Bearden and Casanova, 2016; Sizun et al., 2000; Sakaguchi et al., 2010; Greatorex et al., 2011; Rabenau et al., 2005). In order to prevent the data points from overlapping too much, the data points under the same volume were

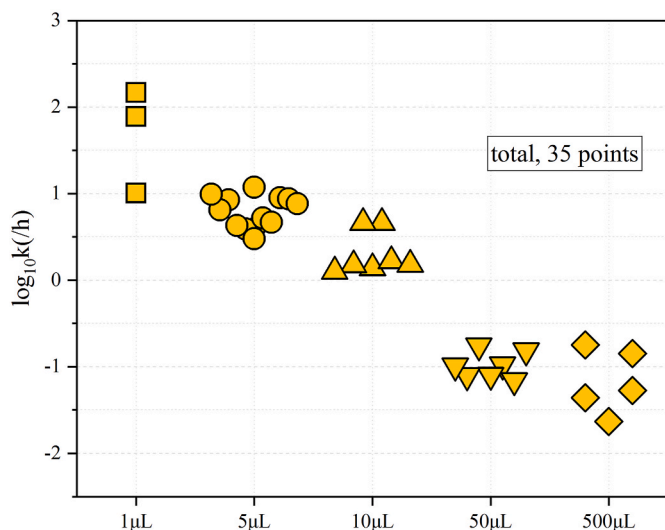


Fig. 4. Relationship between virus decay rate constants and titration volume.

plotted horizontally. Although the titrated volume in the experiments in the literature may be scattered in some places, it is found that the study of the virus decay mechanism in our paper has great theoretical and practical value. It can be seen that the volume of the virus-containing droplet has a very obvious influence on virus decay. With the decrease of the droplet volume, the virus inactivated rapidly. The virus decay rate constants in 1  $\mu\text{L}$  droplets were 3 orders of magnitude larger than in the 500  $\mu\text{L}$  droplets (the significance to the risk of transmission is analyzed later). It was also found that the difference of the decay rate constants of viruses was significantly smaller than that of other single-factor cases under the same titration volume. These measured data strongly proved that the larger the surface droplet volume, the greater the risk of transmission would be, which is the focus of epidemic prevention and control. The droplet size directly affects the physical processes of the viruses on the surface and then has a significant influence on the virus decay. According to relevant studies and tests reported in the related literature research, 1  $\mu\text{L}$  droplet can be dried on the surface for several minutes to reach equilibrium, while 1  $\mu\text{L}$  droplet can be dried for several hours, creating better conditions for the survival of the virus.

Compared with the actual exhaled droplets deposited on the surface from an infected individual, the experimental conditions are more extreme. According to the literature (Lindsley et al., 2012; Bourouiba et al., 2014), respiratory activities (including breathing, talking, coughing, etc.) of patients produced droplets with different particle size distributions, which could be deposited to the surface, ranging from 20 to 1000  $\mu\text{m}$ . The volume of a spherical particle is proportional to the cube of diameter. Even the smallest experimental droplet volume of 1  $\mu\text{L}$  is equivalent to 1900 droplets of 100  $\mu\text{L}$ . It is not difficult to infer that the actual decay rate constant is much larger. However, the viruses survived for several hours or even tens of hours under the existing experimental conditions. It only emphasized the existence and duration of the viral activity, without pointing out the main contradiction and the real risk of transmission, which has only warning significance for the prevention and control of the epidemic.

### 3.4. The effect of surface material on survival

In the indoor and outdoor spaces where infected people live and work, there are various types of surfaces. Large-sized droplets released by respiratory activities such as breathing, talking, and coughing may be deposited on these surfaces. There is abundant experimental literature on the survival of viruses on different surfaces. Van Doremalen et al. (van Doremalen et al., 2020) compared the stability of SARS-CoV-2 and SARS in air and on four common surfaces (copper, cardboard, stainless steel, plastic). The results showed that the exposure time for the detection of live viruses was basically the same, but varied greatly for different surfaces. It took at least 8 h for the copper surface, about 48 h for stainless steel, and 72 h for plastic. Chin et al. (2020) showed that live viruses could not be detected after 3 h of inoculation on printing paper and napkins, whereas viruses could survive on wood surfaces for about 2 days. Fig. 5 shows a representative comparison of the decay rate constants of respiratory viruses on 7 common surfaces, based on 27 experimental results of 7 studies under approximately similar laboratory temperature and relative humidity condition (van Doremalen et al., 2020; Warnes et al., 2015; Chin et al., 2020; Casanova et al., 2010; Bearden and Casanova, 2016; Sakaguchi et al., 2010; Greatorex et al., 2011). It can be seen that the decay rate constants of the viruses on different surfaces vary greatly, and the surface characteristics have a significant impact on the viral survival. On the surface of porous objects such as paper, the virus decay rate constant  $k$  is much higher than that of other types of objects. After the virus suspension was inoculated to such surfaces, most of the water was quickly absorbed by the object. Therefore, the living environment deteriorated rapidly, a large number of viruses on the surface were inactivated, and the decay rate constant was large. For a smooth surface, the virus suspension was roughly spherical and attached to the surface, carrying out slow heat and mass transfer

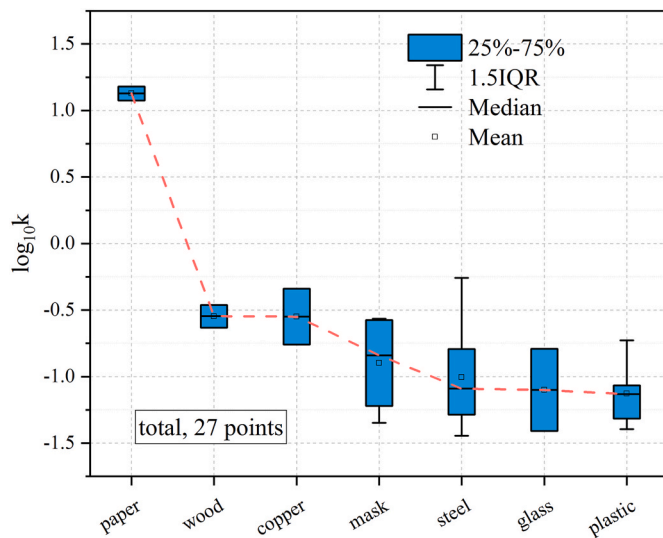


Fig. 5. Virus decay rate constants on the surfaces of different objects.

processes with the surrounding environment. Then the deterioration of the viral living environment was “alleviated”. Under the same circumstances, viruses could survive for a longer time on smooth surfaces, so the virus decay rate constants were generally small. However, there were still some differences between various smooth surfaces. For example, for metal surfaces, the decay rate constant of viruses on copper was obviously greater than that on stainless steel. Furthermore, some scholars have conducted experimental studies and pointed out that the release of copper ionic species promoted the inactivation of viruses and other pathogens, and copper surfaces might play an important role in reducing the transmission risk from contaminated surfaces (Warnes et al., 2015; Warnes and Keevil, 2013; Sagripanti et al., 1997). Therefore, based on this, we recommend the use of copper alloy surfaces in public areas, which may help to reduce infection spread by contact with contaminated surfaces.

### 3.5. The effect of virus species on surface survival

Viruses are the main causes of infection. When studying the survival of viruses on the surface of objects, experiments by different scholars

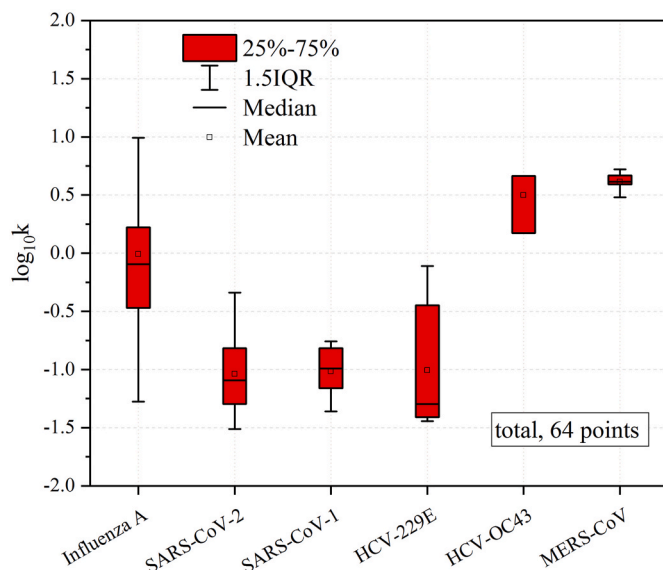


Fig. 6. Distribution of decay rate constants of different viruses.

involved a variety of viruses. The research results can be integrated to analyze the impact of virus types on the viral survival. Fig. 6 shows the distribution of the decay rate constants on the surface of different viruses (van Doremalen et al., 2013, 2020; Warnes et al., 2015; Chin et al., 2020; Sizun et al., 2000; Kratzel et al., 2020; Sakaguchi et al., 2010; Greatorex et al., 2011). It can be seen that the type of virus had an impact on the viral survival on surfaces. For several viruses shown in the curve, MERS-CoV had a larger decay rate constant, indicating that its persistence on the surface of objects was shorter than other viruses. Therefore, the virus inactivation rate was faster on the surface, and the risk of transmission through touching contaminated surfaces was lower. As for SARS-CoV-2, we observed that it had a smaller decay rate constant. This means that the virus could remain active on the surface for a longer time, leading to a higher transmission risk when in contact with contaminated surfaces. This is one of the reasons for the current COVID-19 pandemic and the high risk of transmission. As for influenza A virus, which is a common influenza virus, it is most prone to mutation. Some studies have shown that various strains of the virus might exhibit different viability, which should be taken seriously (Otter et al., 2016). When carrying out surface survival experiments, researchers have involved influenza A viruses of different strains, such as influenza A A/PuertoRico/8/34 (PR8), a/Mexico/4108/2009 (H1N1) virus. The decay rate constants obtained according to the experimental results include the effects of different strains. It can also be seen from Fig. 6 that the value of the decay rate constant of influenza A virus had a wide range distribution, the survival ability of the virus on the surface was different, and the transmission risk was diverse. In reality, people are generally susceptible to it.

## 4. Discussion

We have studied the mechanism of various factors on virus decay through a large number of medical experiments, and reflected on the influence degree of various factors through the decay rate constant. Here we discuss the essence through the phenomenon in order to reveal the main contradiction between the virus transmission risk and disease prevention and control.

### 4.1. The internal relationship between the virus decay rate constant and the relative survival rate of viruses

From Figs. 2–6, it can be seen that the decay rate constants  $\log_{10}k$  were between  $-3$  and  $2$  (that is,  $k$  values were between  $0.001$  and  $100$ ), with a difference of 5 orders of magnitude. The experiments proved that the decay characteristics of viruses on the surface of objects over time are quite different. Some scholars pointed out in experiments on virus persistence on a surface that the curve of virus decay with time showed a two-stage characteristic (Chin et al., 2020; Casanova et al., 2010; Bearden and Casanova, 2016; Sizun et al., 2000). That is, after the viruses deposited on the surface, the viral concentration in the early stage decreased rapidly and became inactive, and then the decrease of the surface viral concentration slowed down and entered another stage of decay. Through the curve of virus concentration change with time, two processes with different decay rates can be clearly observed, and different decay rate constants can be used to describe the different stages.

In order to reveal the essence of the decay law of viruses on the surface of objects, we selected 7  $k$  values within the experimental range and plotted a curve of the relative concentration (survival rate) of viruses with different  $k$  values over time (Fig. 7). The normalization of the relative concentration  $C/C_0$  can avoid the difference of the initial concentration  $C_0$  and better reveal the internal law of the decay rate constant and the change of the virus survival rate. It can be seen that the relative survival rate of viruses decreased rapidly with the increase of the decay rate constant. When the decay rate constant was small, such as  $k = 0.01$ , the relative survival rate of the virus decreased slowly and



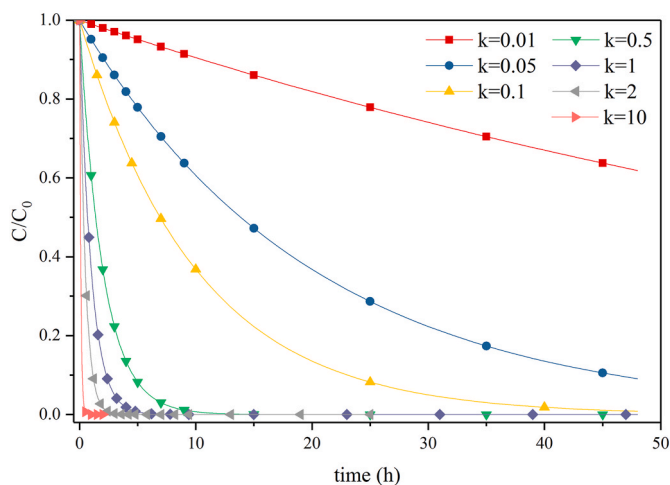


Fig. 7. The change rule of  $C/C_0$  with time under different decay rate constants.

almost linearly. The smaller decay rate constant  $k$  may correspond to the surfaces such as in seafood markets and cold store chains. The temperature, moisture and nutrient conditions in these environments are favorable for the viruses to survive, or to large-sized droplets deposited on the surface. With the increase of the decay rate constant, for example, when  $k = 0.1$ , the viral concentration changed over time showing a two-stage appearance feature. The decay speed of the viruses on the surface can be more obviously observed from large to small. With the continuous increase of the decay constant, the virus survival rate tended to the ordinate. In other words, the viruses decayed in a very short time, corresponding to the small-sized droplet nuclei or the process of disinfection of the viruses. Therefore, the two-stage decay is only a superficial phenomenon, and the virus decay rate constant  $k$  can be used to quantitatively and comprehensively reflect the indicators of the virus viability and transmission risk on the surface.

#### 4.2. Decay rate constant and window period of disease prevention and control

The most important thing for epidemic prevention and control is to recognize the decay law and take decisive and precise measures to achieve immediate results. It can be seen from Fig. 7 that under different decay rate constants  $k$ , the relative survival rate of viruses changed rapidly over time with the combined effects of environmental parameters, surface characteristics, virus types and other factors. For the case of a small  $k$  value, it is necessary to focus on prevention, which is the main contradiction. For a case with a high  $k$  value, it is not the main contradiction of prevention and control, and there is no need to create artificial panic. In the case of a moderate decay constant, the most favorable opportunity should be seized for effective prevention and control. In order to find the window period for prevention and control, we define the time for the change speed of relative concentration  $C/C_0$  to approach 0 (such as 0.001), beginning from viruses deposited on the surface under the combined effects of various factors. According to equation (1):

$$\frac{d(C/C_0)}{dt} = -ke^{-kt} \tag{3}$$

It is not difficult to see from the above equation that the change speed in the relative survival rate decreases exponentially with time. At the initial time  $t = 0$ , the change speed is the highest when the virus-containing droplet just settles on the surface. With the passage of time, the change speed decreases; when given enough time, there are few active viruses on the surface, and the transmission risk is very low. Therefore, this time is defined as the window period for effective control of viral infection on the surface of objects. In order to find the

relationship between this window period and the virus decay rate constant, we selected 7 different decay rate constants and plotted the change rate of virus relative concentration (survival rate) over time under different  $k$  values (Fig. 8). It can be seen that for these cases when  $k \leq 0.1$ , the window period was as high as 50 h and should not be taken lightly; for those cases with  $k \geq 10$ , the window period only took a few hours or minutes; in the case of  $k$  values between 0.5 and 10, the window period must be grasped, and the earlier the better.

#### 4.3. The relationship between the decay rate constant and characteristic time

The decay process of viruses on the surface of objects follows an exponential function. In theory, the time required for the total viruses to decay completely is infinite, and lacks practical significance. In order to reflect the decay of the viruses, it is medically defined that when the virus concentration drops to a certain percentage of the initial concentration (such as 50%, 90%, and 99%), the time required for the process is the characteristic time, expressed in terms of  $t_{50}$ ,  $t_{90}$ ,  $t_{99}$ , etc.

For example, when the virus concentration drops to 90% of the initial concentration, that is, 90% of the virus decay, here  $C/C_0 = 0.1$ , and the characteristic time required for this process,  $t_{90}$ , can be obtained from Equation (1):

$$t = -\frac{\ln(C/C_0)}{k} \tag{4}$$

$$t_{90} = -\ln 0.1/k = 2.3025/k \tag{5}$$

Similarly, we can also calculate the characteristic time  $t_{50}$  and  $t_{99}$  corresponding to the virus concentration reduction of 50% and 99%.

Fig. 9 shows the change of characteristic times  $t_{50}$ ,  $t_{90}$ , and  $t_{99}$  with the decay rate constants. It can be seen that with the increase of the decay rate constant, the characteristic time  $t_{90}$  ( $t_{50}$ ,  $t_{99}$ ) would decrease rapidly. When  $k$  values are small, there is a high risk of virus infection, and it is necessary to focus on prevention and control. If  $t_{90}$  is too large, it means that it would take a long time for the viruses to decay on the surface of objects, indicating that there is a high risk of transmission from touching contaminated surfaces; with smaller  $t_{90}$ , viruses can be inactivated quickly, and the lower the risk of transmission, and the more conducive for disease control.

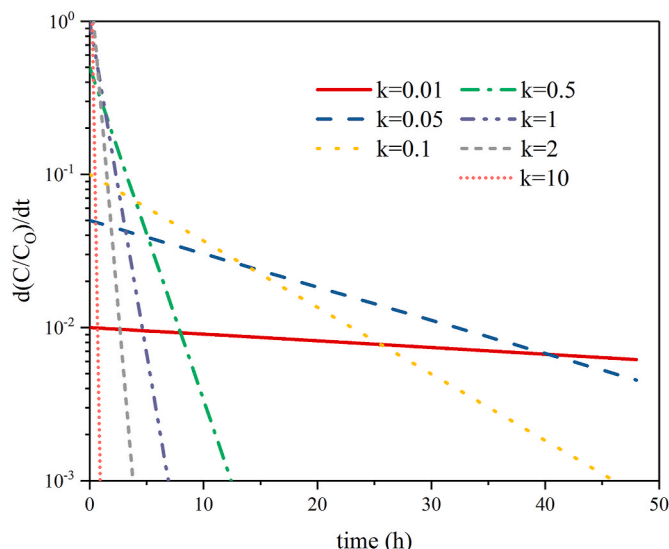


Fig. 8. Change speed with time under different decay rate constants.



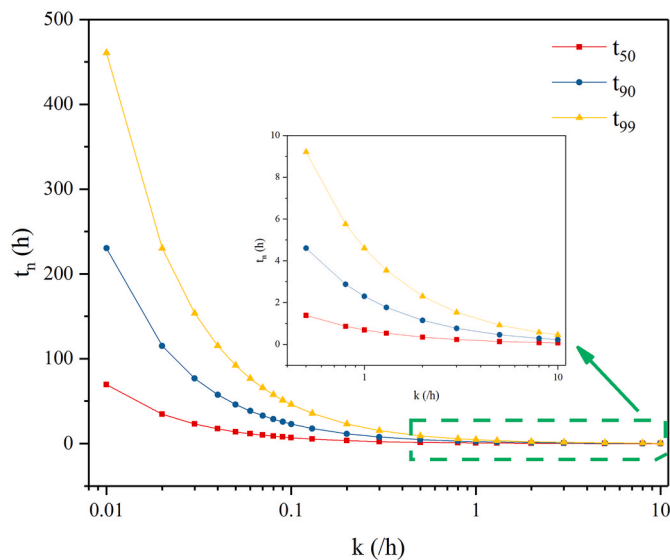


Fig. 9. Change of characteristic time with decay rate constants.

4.4. The decay rate constant revealed the phenomenon and essence of virus decay

Although most of the existing experimental literature described the original concentration of the prepared virus suspension, when presenting the experimental results, the vast majority of the studies did not show it in the curve of virus concentration over time. Scholars usually took the first sampling concentration after the suspension was titrated to the surface (generally 2–5 min after titration) as the initial concentration. According to the law of surface virus decay confirmed by a large number of experiments, it is not difficult to predict that although this time is very short, the surface virus activity will undergo violent decay during this period. Ignoring this important period does not show the whole picture of virus decay, and cannot accurately describe the important process of virus release from the host and settling on the surface. Here, we selected the stability of SARS-COV-2 on glass, banknotes, plastic and the outer layer of a surgical mask for a representative illustration (Chin et al., 2020). Table 1 gives the virus concentration at each time node presented in the literature. Fig. 10 shows the curve of SARS-CoV-2 relative survival rate over time on glass. If the initial suspension concentration is used as  $C_0$ , the relative survival rate of the virus would decrease faster. This is more consistent with the situation where virus-containing droplets are suddenly sprayed from an infected individual and then settle on the surface. We consider that a complete presentation of the initial, intermediate, and later survival of the viruses at each time node could help the public understand the essence of the

Table 1  
Virus concentration at each time point (unit  $\log_{10}TCID_{50}/mL$ ).

Time node	Glass	Banknote	Plastic	Mask, inner layer
Initial suspension concentration	7.8	7.8	7.8	7.8
0 h	5.83	6.05	5.81	5.88
0.5 h	5.81	5.83	5.83	5.84
3 h	5.14	4.77	5.33	5.24
6 h	5.06	4.04	4.68	5.01
24 h	3.48	3.29	3.89	4.21
48 h	2.44	2.47	2.76	3.16
96 h	/	/	2.27	2.47
$k$	0.162	0.152	0.086	0.081
After the titration				
$k$	0.192	0.186	0.101	0.096
Including the initial suspension concentration				

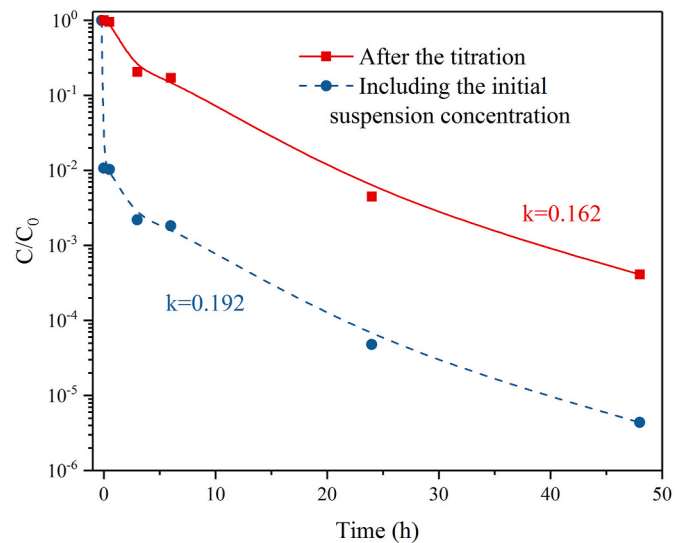


Fig. 10. Differences between the whole process and local process of the virus decay constants.

problem and the transmission risk. In Fig. 10, the decay rate constants obtained from the two initial nodes are given. It can be seen that the decay rate constant including the concentration of the suspension increased significantly, which further confirms the universality of the surface virus decay characteristic. Because even if the first sampling time (or any time after that) is used as the starting point, the pattern of virus decay is common. However, an incomplete presentation may conceal the main contradiction of the virus spread on the surface of objects.

This suggests that, in order to effectively reduce the risk of media transmission on contaminated surfaces, prevention and control should focus on the initial stage after surface were contaminated. Firstly, it is necessary to promote good coughing etiquette, advocate good sanitary habits such as no spitting, frequent hand washing and no eye rubbing, so as to reduce the sources of infection; secondly, using disinfectants to clean surfaces frequently, where people are active, and removing the source of infection as soon as possible.

The law of virus decay over time suggests that the earlier the time, the more important is the prevention and control, otherwise the window period of prevention and control would be fleeting. If, at the later stage, the risk has been greatly reduced, there is no need for unnecessary panic. In terms of the mechanism, when the decay rate constant is large (small-sized droplets), the key to prevention and control is to focus on the source (wearing masks, keeping social distancing) and the early stage. The risk is very low in the later stage, and the public can deal with it calmly without panic. Low  $k$  values of the decay rate constant (seafood markets, cold chain logistics and other places coupled with low temperature and low humidity, low temperature and high humidity environment) should be paid special attention. According to the change law of virus decay with time on the surface of objects, cleaning and disinfection are important. The essence of disinfection is to greatly increase the decay rate constant through human intervention. Disinfection should be carried out, the sooner the better. Failure to grasp the principal contradiction of disinfection is tantamount to doing useless work. For example, it will do more harm than good to disinfect the surfaces of general indoor objects, municipal facilities and air conditioning systems.

5. Conclusions

Exposure to contaminated surfaces is one of the main routes of respiratory diseases transmission. The influence of various factors on the virus decay rate constant  $k$  was comprehensively analyzed through

existing virus survival experiments. The main conclusions are as follows:

Firstly, the virus concentration followed an exponential decay law characterized by the decay rate constant under the influence of various factors. The  $k$  values ranged from 0.001 to 100 h<sup>-1</sup> under different experimental conditions, with a difference of 5 orders of magnitude. Moreover, the characteristic time  $t_{99}$  was between 500 and 0.1 h, indicating the huge differences on the transmission risk in different situations.

Secondly, in terms of environmental impact, the virus decay rate constant  $k$  increased gradually as the ambient temperature rose from 4 °C. Viruses in dry or humid environments had lower decay rate constants, while in moderate relative humidity environments (30–60% RH) the  $k$  values were higher. This shows that it is unreasonable to blindly suggest that heating should be stopped during the epidemic to reduce the risk of virus transmission.

Thirdly, in terms of droplet size and surface materials, the virus decay rate constant  $k$  in 1 µL droplets was 3 orders of magnitude larger than that in 500 µL droplets, and the virus decay on water absorbing surfaces was much higher than that on smooth surfaces. It not only revealed that the physical process of water evaporation and component concentration of droplets had a vital influence, but also proved that the main contradiction of disease prevention and control by the contaminated surfaces was the large-sized droplet. Intense respiratory activities, such as spitting, coughing and sneezing should be given special attention.

Furthermore, the characteristic time  $t_{50}$ ,  $t_{90}$ , and  $t_{99}$  can intuitively indicate the speed of the virus decay. A quantitative expression of the decay rate constant  $k$  and each characteristic time was provided. With the increase of  $k$  values, the characteristic times  $t_{90}$  ( $t_{50}$ ,  $t_{99}$ ) would decrease rapidly.

By revealing the common law and individuality of virus decay on the surface of objects, it was pointed out that there was great difference on the virus transmission risk at different time nodes. The suggestions of prevention and control strategies in grasping the principal contradiction under different circumstances are given. At the initial stage of droplets deposition on the surfaces, there were higher transmission risk. Therefore, if the control measures are taken earlier, the effect is immediate. Later, the risk was smaller, and blind disinfection would do more harm than good. It is possible to identify situations in which the decay rate constant of the viruses may be very small (e.g. seafood markets, logistics cold chains, slaughterhouses, surfaces with a specific range of temperature and humidity), which are the focus of disease spread. Where the virus decay rate constants may be small (such as in outdoor municipal facilities surfaces), there is no need to panic.

#### Credit author statement

Luyao Guo: Conceptualization, Methodology, Investigation, Writing – original draft. Zhao Yang: Investigation; Writing – review & editing, Supervision. Lei Guo: Writing – review & editing, Supervision. Linlin Chen: Writing – review & editing, Supervision. Li Zhang: Supervision, Funding acquisition. Enshen Long: Conceptualization, Methodology, Investigation, Writing – review & editing, Project administration, Funding acquisition.

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#### Declaration of competing 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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