Saliva Droplet Evaporation Experiment and Simple Correlation of Evaporation-falling Curve under Different Temperatures and RH

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ABSTRACT

In the present study, water and saliva droplet evaporation rates are experimentally evaluated in various environmental conditions: temperature and relative humidity. We found that the ratio of saliva residue size to saliva initial droplet size is 0.216. We also found that the saliva correction factor which is defined as a ratio of water evaporation coefficient to saliva evaporation coefficient was not affected by environmental conditions and was determined as 0.857. By considering the evaporation and gravitational settling effects, the saliva airborne lifetime, i.e., the evaporation-falling curve is numerically calculated and characterized. In addition to this numerical calculation results, we present the simple correlation equation for obtaining the evaporation-falling curve under different temperatures and relative humidity.

Keywords: SARS-CoV-2, Evaporation-falling curve, Saliva evaporation

1 INTRODUCTION

Social distancing and punitive measures to prevent the spread of COVID-19 through human-to-human transmission are having a huge impact on the environment, health, and economy (Sarkodie and Owusu, 2021). Despite the current growing vaccination rates, the continuous emergence of newly mutated viruses such as Beta, Delta, and Omicron variants makes it difficult to prevent virus transmissions. As of January 9, 2023, there were more than 657 million confirmed cases and 6.6 million reported deaths worldwide due to COVID-19 (WHO, 2023). In addition, the recent study (Liu et al., 2021) has shown that omicron variants can evade the immune protection conferred by vaccines and natural infections. Therefore, as the current serious COVID-19 pandemic is getting worse, not only social measures like social distancing and border restrictions but also academic research to mitigate the risk of SARS-CoV-2 virus transmission is still required.

Centers for Disease Control and Prevention (CDC) claims that there are three main routes for people to become infected with SARS-CoV-2 by infectious virus-laden respiratory droplets: (1) inhalation of fine respiratory droplets or aerosol particles, i.e., airborne transmission; (2) deposition of respiratory droplets in the mouth, nose, or eyes, i.e., droplet transmission; (3) touching mucous membranes with dirty hands (direct contact with respiratory fluid or indirect touch viral contaminated surfaces), i.e., fomite transmission. Recently, to mitigate SARS-CoV-2 transmission, various methods like room ventilation (Dao and Kim, 2022; Faulkner et al., 2022; Cao et al., 2021; Chen et al., 2021), surface decontamination (Kim et al., 2021; Kwak et al., 2021a), and wearing facial masks (Fakir and Kim, 2022; Ou et al., 2020) are suggested. Even though there is a controversial discussion regarding the dominant SARS-CoV-2 transmission route, airborne or droplet transmission plays a vital role in the spread of diseases (Cheng et al., 2022; Lai et al., 2020; Wan et al., 2009). People can produce a considerable amount of respiratory droplets like...
saliva during exhalation, e.g., breathing, talking, singing, coughing, and sneezing [Edwards et al., 2021; Alsved et al., 2020; Asadi et al., 2019, 2020; Eckernach et al., 2020; Stadnytskyi et al., 2020; Morawska et al., 2009; Xie et al., 2009; Yang et al., 2007; Duguid, 1946]. For determining the risk of airborne or droplet transmission of SARS-CoV-2, the airborne lifetime of respiratory droplets should be estimated.

Various methods were employed for determining saliva droplet size distribution, even though there are significant discrepancies between previous studies. By using an aerodynamic particle sizer, Alsved et al. (2020) measured exhaled respiratory droplets during the singing and talking and revealed that most of the droplets are 0.5–0.7 μm. By using the solid impaction method, Duguid (1946) reported that 95% of respiratory droplets were produced between 2 μm and 100 μm when coughing or sneezing and Xie et al. (2009) reported that the average size of saliva droplets during coughing and sneezing was approximately 50–100 μm. By using an aerodynamic particle sizer and scanning mobility particle sizer, Yang et al. (2007) reported that respiratory droplets ranging from 0.62 to 15.9 μm with an average mode of 8.4 μm were produced by coughing. Han et al. (2013) investigated particle size distribution of the droplets exhaled by sneezing using a laser particle size analyzer and found two different distributions from twenty subjects: the geometric mean sizes for unimodal distribution, and bimodal distribution were 360.1 μm, and 74.4 μm, respectively. By using the interferometric Mie imaging technique, Chao et al. (2009) reported that geometric mean sizes of respiratory droplets were 13.5 μm for coughing, and 16 μm for talking.

Respiratory droplet residue is the final product of a respiratory droplet after complete evaporation produced by the atomization of human secretions along the airway (Liu et al., 2017; Hare, 1964). Numerous studies on the evaporation of water have previously been conducted. Al-Shammmari (2002) investigated the effects of salinity on water evaporation by measuring the evaporation rate of distilled water, sea water (34,000 ppm), and two brine solutions of 56,000 and 69,000 ppm. Furthermore, Zhang (2011) also explored the correlation between salinity and evaporation as well as the effects of varied relative humidity and temperature conditions on evaporation. Both confirmed that an increase in salinity will result in a decrease in the evaporation rate. Zhang (2011) also determined that altering relative humidity with a constant temperature will be inversely related while altering temperature with constant relative humidity and the water evaporation rate provides an inconclusive relationship. However, Liu et al. (2017) found through a cough jet that medium-sized droplets, around 60 μm, are more influenced by humidity than smaller and larger droplets. A study by Hisatake et al. (1993) explored the evaporation rate of water within a vessel, undergoing varied vessel diameter, relative humidity, temperature, and air velocity. By comparing the theory of water vapor evaporation rate through the boundary layer covering the water surface in a vessel to experimental results, Hisatake et al. (1993) found that the theory provides good estimates. Other variables of environmental conditions have also been analyzed.

In this study, saliva evaporation characteristics, which are very important for understanding the airborne transmission of SARS-CoV-2, were experimentally observed under various ambient conditions (20% ≤ RH ≤ 70%, 15°C ≤ T ≤ 30°C). To depict saliva in the air, a microgravity environment was implemented using an acoustic levitator. By comparing the evaporation characteristics of saliva obtained through the experiment with that of water, the data were quantified in two aspects: (1) residue size obtained after complete evaporation of saliva; (2) ratio of saliva evaporation coefficient. Using the results obtained through the experiment, the evaporation-falling curve was obtained through numerical analysis, and a simple correlation curve that can obtain the evaporation-falling curve without numerical analysis was presented. The simple correlation of the evaporation-falling curve is expected to be utilized to determine the risk of airborne virus transmission in various atmospheric conditions without complicated calculations.

## 2 EXPERIMENTAL METHOD

The experimental setup used to measure the change of droplet sizes during evaporation was illustrated in Fig. 1. The acoustic levitator (Tec5 AG, Oberursel, Germany) was used for floating the droplets in the air without contacting the surface. Droplets can be suspended in a standing wave which is generated from caused by multiple reflections between a piezoelectric transducer and a concave reflector, resulting from the balance of gravity and forces caused by axial acoustic
pressure. In our tested condition, droplets with diameters of 100–1000 µm can be suspended. The acoustic levitator was placed in a controlled environmental chamber (Environmental Growth Chamber, GCW15, Chargin Falls, OH, USA). The evaporation process of acoustically levitated saliva or water was recorded by a microscope camera with a 300X industry zoom C-mount lens (HY-2307K, Hayear Electronics, Shenzhen, China). The temperature and relative humidity inside the environmental chamber changed from 15°C to 30°C and from 20% to 70%, respectively, so that a total of 28 conditions were tested.

To obtain the size evolution during the droplet evaporation, the images were acquired every second. For handling lots of images obtained from the microscope camera, the images were processed with a certain rule by using ImageJ 1.53e software (Schneider et al., 2012), as shown in Fig. 2(a). The original images of Fig. 2 show a distinct oval shape in the middle of the levitated droplets due to the light refracted from the vertically installed LED light in Fig. 1(b). For finding the edges of droplets, the Sobel edge detector algorithm which measures 2D spatial gradient on images was implemented, resulting in distinguishing the droplets and background noise. For calculating the droplet size based on the droplet projected area, RGB color images need to be binary images. Through averaging each RGB value of images, 8-bit grayscale images were obtained.

Fig. 1. (a) Environmental chamber to control temperature and relative humidity and (b) experimental setup to measure changes in the size of acoustically levitated water or saliva droplets during evaporation.

Fig. 2. (a) Flow chart of the image processing algorithm and (b) examples of obtained binary image and droplet size through the image processing algorithm. The scale bar indicates 100 µm.
By comparing 16 different auto thresholds in *ImageJ* software, the triangle method (*Zack et al., 1977*) was chosen for converting 8-bit grayscale images to binary images. Based on the outline of binary images, the images are filled with white color. The droplet sizes were determined by the projected area of binary images. Fig. 2(b) shows examples of obtained binary images and corresponding droplet diameters. Some images were not analyzed when blur images were obtained due to shaking droplets as presented in Fig. S2 in the Supplementary Information.

### 3 EVAPORATION MODELING

For smaller Knudsen numbers, the evaporation depends on the diffusion rate of molecules on the droplet surface. The rate of evaporation can be expressed as follows *(Niimura and Hasegawa 2019; Frohn and Roth, 2000; Hinds, 1982):*

\[
\frac{d(d_p)}{dt} = \frac{4DM}{R\rho_p d_p} \left( \frac{p_{v,w}}{T_s} - \frac{p_{v,s}}{T_s} \right) \phi_{\text{saliva}} 
\]

where \(d_p\) is droplet diameter, \(D\) is diffusion coefficient, \(M\) is the molecular weight, \(R\) is the gas constant of 8.3145 J mol\(^{-1}\) K\(^{-1}\), \(\rho_p\) is the droplet density, \(p_{v,w}\) is the partial vapor pressure remote from the droplet surface, i.e. ambient partial vapor pressure, \(p_{v,s}\) is the partial vapor pressure at the droplet surface, \(T_s\) is ambient temperature, \(T_s\) is droplet surface temperature, and \(\phi\) is the correction factor due to experimental conditions. To compensate for the difference between water and saliva evaporation, the saliva correction factor \(\phi_{\text{saliva}}\) was introduced. In the present study, since the test substances were water and saliva (which contains water 99.5%) *(Radha et al., 2016; Schipper et al., 2007)*, several physical parameters can be estimated *(Huang, 2018; Kukkonen et al., 1989; Hinds, 1982):*

\[
D = 0.22 \times 10^{-4} \left( \frac{T_s}{273.15} \right)^{1.67} \left( \frac{101325}{P_{\text{amb}}} \right) 
\]

\[
\rho_p = 1050 - 0.1763T_s 
\]

\[
\rho_{v,sat} = \frac{\exp\left(34.494 - \frac{4924.99}{T_s - 36.05}\right)}{(T_s - 168.15)^{1.57}} 
\]

\[
T_s = T_s + \frac{\left(6.65 + 0.345(T_s - 273.15) + 0.0031(T_s - 273.15)^2\right)(S_R - 1)}{1 + \left(0.082 + 0.00782(T_s - 273.15)\right)S_R} 
\]

and

\[
S_R = \frac{p_{v,w}}{p_{v,sat}} 
\]

Here, \(P_{\text{amb}}\) is ambient pressure, \(p_{v,sat}\) is saturation vapor pressure, and \(S_R\) is the saturation ratio. The correction factor for the acoustic levitation experiment \(\phi\) is suggested as a function of the Sherwood number *(Schiffter and Lee, 2007; Tuckermann et al., 2002)*. It should be noticed that the correction factor for the acoustic levitation experiment proportionally increases with the intensity of the ultrasonic field *(Tuckermann et al., 2002)*. For our conditions, the correction factor was determined to be 1.1552, as presented in Fig. S2 in the Supplementary Information. Through integrating Eq. (1) with respect to time, the rate of evaporation which is not influenced
Fig. 3. Results of water droplet evaporation experiment at $T = 20^\circ C$ and RH = 25%. (a) Droplet diameter as a function of time for five droplets with various initial droplet diameters. (b) Evolution of $(d_p^2/d_{p,o}^2)$ as a function of $4t/d_{p,o}^2$ with five different initial droplet diameters. T, temperature; RH, relative humidity; $d_p$, droplet diameter; $d_{p,o}$, initial droplet diameter; $t$, time.

by the different initial droplet sizes can be expressed as follows:

$$\frac{d_p^2(t)}{d_{p,o}^2} = 1 - \frac{2DM}{R\rho_p} \left( \frac{P_{v,\text{sat}}}{T_{\text{droplet@surf}}} - \frac{P_{v,\infty}}{T_\infty} \right) \phi_{\text{saliva}} \frac{4t}{d_{p,o}^2}$$

(7)

To simplify the dimensionless Eq. (7), the evaporation coefficient ($\beta_v$) was introduced. The evaporation coefficient ($\beta_v$) and the simplified dimensionless Eq. (7) are as follows:

$$\beta_v = \frac{2DM}{R\rho_p} \left( \frac{P_{v,\text{sat}}}{T_{\text{droplet@surf}}} - \frac{P_{v,\infty}}{T_\infty} \right) \phi_{\text{saliva}}$$

(8)

and

$$\frac{d_p^2(t)}{d_{p,o}^2} = 1 - \beta_v \phi \frac{4t}{d_{p,o}^2}$$

(9)

If the vapor pressures and temperatures slowly change during the evaporation experiment, the evaporation coefficient is nearly constant in time. As shown in Fig. 3, it can be seen that dimensionless Eq. (7) (or Eq. (9)) is not affected by different initial droplet sizes under the same temperature and relative humidity conditions, which characteristic is known as the $d^2$-law. It should be noted that the slope in Fig. 3(b) indicates the corrected evaporation coefficient ($\beta_v\phi$). Thus, the simplified dimensionless equation (i.e., Eq. (4)) allows a direct comparison of the water and saliva droplet evaporation process with different initial sizes.

4 RESULTS AND DISCUSSION

Fig. 4 shows the evaporation process of acoustically levitated pure water and saliva droplets at a temperature of 20\(^\circ\)C and a relative humidity of 50%. Because the evaporation process takes place at the droplet surface, both water and saliva droplets evaporate at the rate proportional to the surface area, resulting in a constant slope (i.e., evaporation coefficient) regardless of time, as shown in Fig. 4(b). However, two distinct evaporation characteristics of saliva compared to pure water were confirmed: (1) before about 600 seconds, the slope in Fig. 4(b) was slightly less steep
than that of pure water; (2) after about 600 seconds, saliva did not evaporate any more, unlike pure water, and created a residue particle. Therefore, this study describes the characteristics of saliva residue in Section 4.1 and compares water and saliva evaporation coefficients in Section 4.2.

### 4.1 Saliva Residue

Under a temperature between 15°C and 30°C and relative humidity between 20% and 70%, 32 saliva droplet samples with saliva initial droplet size ranging from 338 µm to 974 µm were tested for determining the ratio of saliva residue size to saliva initial droplet size, i.e., $\psi = d_{p,\text{residue}}/d_{p,\text{o}}$.

Nicas et al. (2005) predicted the saliva residue size to be about half that of the initial saliva droplet ($\psi \approx 0.5$), using the saliva composition data by Effros et al. (2002). Liu et al. (2017) suggested that when the initial salt mass fraction was 0.9% and the initial solid volume ratio was 1.8%, the
ratio of the saliva residue to the initial saliva droplet size was 0.32 \( (\psi = 0.32) \). However, it is worthwhile to mention that according to Radha \textit{et al.} (2016)'s studies and Schipper \textit{et al.} (2007)'s review, the saliva composition of solid constituents which includes inorganic solids (e.g., NaCl) and organic solids (e.g., mucin, serum) is only 0.5%. Therefore, both model (Liu \textit{et al.}, 2017; Nicas \textit{et al.}, 2005) needs to be further improved for predicting the ratio of saliva residue size to saliva initial droplet size.

Recently, the average ratios of saliva residue size to saliva initial droplet size measured by Lieber \textit{et al.} (2021) and Stiti \textit{et al.} (2022) were 0.198, and 0.235, respectively. The results of saliva residue diameter \( (d_{p,\text{residue}}) \) as a function of saliva initial droplet diameter \( (d_{p,o}) \) in Fig. 5. The average value of present measurement data corresponded to a ratio \( (\psi) \) of 0.216, and the coefficient of determination \( (R^2) \) was 0.988. When comparing the average ratios \( (\psi) \) with other studies, our measurement values are considered to be reliable. In addition, although the effect of temperature, relative humidity, and initial droplet size was examined, any relation between ratio \( (\psi) \) and other parameters \( (RH, T, \text{ and } d_{p,o}) \) was not found as presented in Fig. S3 in Supplementary Information. Therefore, regardless of other parameters \( (i.e., RH, T, \text{ and } d_{p,o}) \), the ratio of saliva residue size to saliva initial droplet size is fixed to be 0.216 \( (\psi = 0.216) \).

### 4.2 Saliva Evaporation Coefficient

Fig. 6 shows the water and saliva evaporation coefficients as a function of relative humidity and temperature, respectively. As the relative humidity increases, the evaporation coefficient decreases almost linearly. This is because the smaller the amount of water vapor in the atmosphere, the more water vapor the atmosphere can receive from the droplet surface, so the lower the relative humidity, the faster the droplet evaporates, resulting in a higher evaporation coefficient value. On the other hand, as the temperature increases, the number of evaporating water molecules increases because the water molecules move more vigorously at high temperatures \( (i.e., \text{high diffusion coefficient}) \). Therefore, the evaporation coefficient increases as the temperature increases. In addition, Eq. (8) for obtaining the water evaporation coefficient shows that the water evaporation coefficient can be analytically obtained without much error from the experimental results, as shown in Fig. 6.
As illustrated in Fig. 6, it can be seen that under the same conditions, the evaporation coefficient of saliva droplets was mostly measured lower than that of water droplets (i.e., the saliva droplet slightly slowly evaporates compared to the water droplet). This is attributed to the fact that the ions and proteins in saliva create an attraction, resulting in preventing water molecules from going into the atmosphere. The water evaporation coefficient ($\beta_{v,\text{water}}$) and the saliva evaporation coefficient ($\beta_{v,\text{saliva}}$) were compared to obtain the saliva correction factor ($\phi_{\text{saliva}}$), as illustrated in Fig. 7. The effect of temperature and relative humidity on the evaporation coefficient is presented in Fig. S4 in Supplementary Materials. Any relation between (saliva evaporation coefficient) and (RH, and $T$) was not found under the tested conditions ($20% \leq \text{RH} \leq 70%, 15^\circ\text{C} \leq T \leq 30^\circ\text{C}$).

Fig. 6. Effect of (a) relative humidity at $T = 20^\circ\text{C}$ and (b) temperature at RH = 40% on the evaporation coefficient ($\beta_v$). The red solid line which is denoted as water theory was calculated using Eq. (8).

Fig. 7. Comparison of water and saliva droplet evaporation coefficient. The red dashed line represents the linear fitting curve ($\phi_{\text{saliva}} = 0.857, R^2 = 0.984$). $\phi_{\text{saliva}}$, saliva correction factor.
Because the saliva evaporation coefficient is assumed to be independent of RH and T for our tested conditions, the saliva correction factor can be assumed to be a ratio of water evaporation coefficient to saliva evaporation coefficient, i.e., \( \phi_{\text{saliva}} = \beta_{v,\text{saliva}} / \beta_{v,\text{water}} \). The saliva correction factor was determined to be 0.857 with a high coefficient of determination (\( \phi_{\text{saliva}} = 0.857, R^2 = 0.984 \)). By using this factor, the saliva droplet evaporation in the air can be calculated.

### 4.3 Characteristics of Saliva Airborne Lifetime

For predicting airborne lifetime (\( t_{\text{life}} \)), the quiescent ambient conditions are assumed. The settling velocity (\( V_T \)) in quiescent ambient conditions can be calculated depending on Reynolds number (\( Re_p = \rho V T_d / \mu \)). If particle or droplet size approaches the mean free path of the gas, slip phenomena occurs at the surface the particles. To account for the slip effect in Stoke’s law, the slip correction factor was (\( C_c \)) introduced. For particle motion with \( Re_p > 1.0 \), settling velocity should be determined by equating the general form of Newton’s resistance to the force of gravity (Hinds, 1982). Therefore, the settling velocity can be formulated as follows:

\[
V_T = \begin{cases} \frac{4(\rho_p - \rho_g) d_p g}{3 C_D \rho_g} & (Re_p \geq 0.1) \\ \frac{(\rho_p - \rho_g) d_p^2 C_c g}{18 \mu} & (Re_p < 0.1) \end{cases}
\] (10)

Here, the correlation of the drag coefficient (\( C_D \)) (Hinds, 1982) and slip correction factor (\( C_c \)) (Kwak et al., 2020, 2021b, 2023; Kim et al., 2005) can be calculated as

\[
C_D = \frac{24}{Re_p} \left( 1 + 0.15 Re_p^{0.687} \right)
\] (11)

and

\[
C_c = 1 + Kn \left( 1.165 + 0.483 \exp \left( -\frac{0.997}{Kn} \right) \right)
\] (12)

where \( Kn \) is Knudsen number (\( Kn = 2 \lambda / d_p \)). It is worthwhile to mention that the trial-and-error solution should be employed for obtaining settling velocity for large Reynolds numbers (\( Re_p \geq 1.0 \)). The detailed airborne lifetime calculation process and method are described in Fig. 8. The airborne lifetime without evaporation, and after perfectly evaporated can be calculated as follows:

\[
t_{\text{life},o} = \frac{y^*}{V_{T,o}}
\] (13)

and

\[
t_{\text{life},r} = \frac{y^*}{V_{T,r}}
\] (14)

where \( V_{T,o} \) and \( t_{\text{life},o} \) are the settling velocity and airborne lifetime without evaporation, i.e., \( d_\rho(t) = d_{p,o} \), respectively. \( V_{T,r} \) and \( t_{\text{life},r} \) are the settling velocity and airborne lifetime after completely evaporated, i.e., \( d_\rho(t) = \phi_{\text{saliva}} d_{p,o} \), respectively. \( y^* \) is the height above the ground. The time taken for complete evaporation (\( t_{\text{evap}} \)) (i.e., the time it takes to evaporate from the initial droplet size to the residue size) can be determined as follows:
Fig. 8. Flow diagram for obtaining the saliva evaporation-falling curve.

\[
t_{\text{eva}} = \frac{1 - \psi^2}{4 \beta \bar{d}_{\text{po}}^2}
\]  

(15)

To investigate the effect of saliva initial droplet size on airborne lifetime, the classical Wells’ evaporation-falling curve (Wells, 1934) was reproduced under the temperature of 25°C, relative humidity of 0%, and height of 2 m, as shown in Fig. 9. The initial saliva droplet diameters ranging from 1 µm to 500 µm were divided with a logarithmic constant interval of 0.02. Fig. 9 can be divided into three regimes (e.g., Regime I, II, and III) according to dominant effects. In Regime I (effect of residue size), the initial droplet size is so small that the time taken for complete evaporation \( t_{\text{eva}} \) is much less than 10 seconds. Therefore, when the initial droplet diameter is smaller than 50–70 µm, the saliva airborne lifetime is almost equal to the time it takes to reach the ground by free-falling as the residue size \( t_{l,r} \), green dash-dotted line in Fig. 9, resulting in the airborne lifetime of more than 300 seconds. In Regime III (effect of initial droplet size), complete evaporation takes more than 10 seconds due to the large initial droplet size. The settling velocity is too large, so it is hardly affected by evaporation. Therefore, the airborne lifetime is approximately equal to the time it takes to reach the ground by free-falling as the initial droplet size \( t_{l,o} \), purple dashed line in Fig. 9. In Regime II (transition), the time it takes for complete evaporation and the time it takes to reach the ground by free-falling as the initial droplet size
Fig. 9. Results of calculated saliva airborne lifetime, i.e., evaporation-falling curve (red open symbol), saliva airborne lifetime as initial droplet size (purple dashed line), saliva airborne lifetime as residue size (green dash-dotted line), and time taken to completely evaporate (blue solid line) under the temperature of 25°C and relative humidity of 0%. Regime I, II, and III can be categorized by dominant effects: Regime I, the effect of residue size; Regime II, transition; Regime III, the effect of initial droplet size.

are not significantly different. Thus, a combined results of the two effects (residue size and initial droplet size) is shown. According to a van Doremalen (2000)’s study, the half-lives of SARS-CoV-2 in aerosols were approximately 4000 seconds, corresponding to the airborne lifetime of initial saliva droplets diameter of ~20 µm. This indicates that respiratory droplets with an initial diameter smaller than 20 µm will mostly contribute to airborne transmission due to their long airborne lifetime as well as long virus survival time. For respiratory droplets with an initial diameter larger than 100 µm, they will deposit on the ground or object surface due to a short airborne lifetime of fewer than 10 seconds, contributing mostly to fomite transmission. It is worthwhile to mention that once saliva droplets deposit on surfaces, the half-lives of SARS-CoV-2 dramatically increased (e.g., 1.09 hours in aerosols; 3.46 hours in cardboard; 5.63 hours in steel; 6.81 hours in plastic) (van Doremalen et al., 2020).

Fig. 10 shows the effect of temperature and relative humidity on the saliva airborne lifetime. As temperature increases or relative humidity decreases, the time taken to completely evaporate (blue line in Fig. 10) decreases. The time it takes to reach the ground by free-falling to either the residue size ($t_{life,r}$, green line in Fig. 10) or the initial droplet size ($t_{life,o}$, purple line in Fig. 10) is not significantly affected by ambient conditions (e.g., temperature and humidity). However, in Regime II (transition), the ambient conditions have a large influence on the saliva airborne lifetime. For example, for an initial saliva droplet size of 79.4 µm, when the temperature was increased from 10°C to 30°C, the saliva airborne lifetime at RH = 30% increased from 99 to 172 seconds. On the other hand, when the relative humidity was changed from 10% to 70%, the saliva airborne lifetime at $T = 20°C$ was greatly reduced from 166 to 18 seconds. The reason that the saliva airborne lifetime rapidly changes in Regime II according to temperature and relative humidity is that it is more affected by the evaporation coefficient than in the other two Regimes.

To predict the saliva airborne lifetime without complicate calculation which is presented in Fig. 8, the simple correlation equation was introduced. As shown in Fig. 8, the saliva airborne lifetime in Regimes I and III is almost the same as in $t_{life,r}$ and $t_{life,o}$, respectively, and in Regime II, the graph has an inverted S-shaped curve. Therefore, a correlation equation was created by slightly modifying the sigmoid function. The saliva airborne lifetime (i.e., evaporation-falling curve) can be predicted by using a simple correlation equation as follows:
Fig. 10. Effect of (a) temperature at RH = 30% and (b) relative humidity at T = 20°C on saliva airborne lifetime (red), and time taken to completely evaporate (blue). T, temperature; RH, relative humidity.

\[
\log_{10} t_{\text{life,cor}} = \log_{10} t_{\text{life,o}} + \frac{\log_{10} \left( \frac{t_{\text{life,o}}}{t_{\text{life,r}}} \right)}{1 + \exp \left( -A \left( \log_{10} \left( \frac{d_p}{d_r} \right) - B \right) \right)}
\]

(16)

where \( d_p^* \) is droplet diameter when the completely evaporated time (\( t_{\text{eva}} \)) and an airborne lifetime without evaporation (\( t_{\text{life,o}} \)) is the same, i.e., \( d_p \) at \( t_{\text{eva}} = t_{\text{life,o}} \). The correlation constants in Eq. (16) were determined as \( A = 30 \), and \( B = 0.05 \) for the height above the ground (\( y' \)) of 2 m. As shown in Fig. 11, there is almost no difference between correlation calculation results and numerical calculation results. More detailed comparison results between correlation and numerical calculation are presented in Fig. S5 in Supplementary Materials. The error is less than 0.7% for Regimes I and III and less than 2.2% for Regime II. It is worthwhile to mention that it takes about 1–3 hours to calculate by numerical method with a personal computer (2.8-GHz-CPU, Matlab 2018a), but it takes about a few seconds when calculating through the correlation equation.
5 CONCLUSIONS

In the present study, we compared the characteristics of water and saliva evaporation phenomena by using a levitator. To carefully control and adjust the temperature and relative humidity conditions, all experiments were performed in the environmental chamber. The image processing algorithm was developed to obtain the size evolution during droplet evaporation. By introducing a dimensionless evaporation equation, the evaporation coefficients of water and saliva are defined. The experimentally obtained water evaporation results showed that the initial droplet sizes under the same environmental condition were less affected by the evaporation coefficients, i.e., the experimental results well follow the $d^2$-law.

Under the evaporation experiment condition of a temperature ($T$) between $15^\circ C$ and $30^\circ C$, relative humidity ($RH$) between 20% and 70%, and saliva initial droplet size ($d_{p, o}$) ranging from 338 $\mu m$ to 974 $\mu m$, we found the following things:

1) After the volatile liquids inside the saliva droplets are evaporated, the saliva residues are created. Regardless of other parameters (i.e., RH, $T$, and $d_{p, o}$), the ratio of saliva residue size to saliva initial droplet size is fixed to be 0.216 ($\psi = 0.216, R^2 = 0.988$).

2) Saliva droplet slowly evaporates compared to water droplet due to attraction by ions/proteins in saliva droplet. By comparing water and saliva droplet evaporation coefficients, the saliva correction factor was determined to be 0.857 ($\phi_{saliva} = 0.857, R^2 = 0.984$).

3) Due to the slower evaporation rate and residue of saliva droplets, the lifetime of saliva droplets is expected to be longer than water droplets.

The detailed evaporation-falling curve calculation method is presented. For obtaining the saliva evaporation-falling curve, the authors recommend using the numerical calculation method which is presented in Fig. 8 if the readers want to calculate more accurate results, otherwise, we recommend for readers who want to see the general trend of the evaporation-falling curve according to various environmental conditions to use Eq. (16).

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SUPPLEMENTARY MATERIAL

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