

ORIGINAL ARTICLE

Risk assessment of banknotes as a fomite of SARS-CoV-2 in cash payment transactions

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Abstract

The COVID 19 pandemic has triggered concerns and assumptions globally about transmission of the SARS-CoV-2 virus via cash transactions. This paper assesses the risk of contracting COVID-19 through exposure to SARS-CoV-2 via cash acting as a fomite in payment transactions. A quantitative microbial risk assessment was conducted for a scenario assuming an infectious person at the onset of symptoms, when virion concentrations in coughed droplets are at their highest. This person then contaminates a banknote by coughing on it and immediately hands it over to another person, who might then be infected by transferring the virions with a finger from the contaminated banknote to a facial mucous membrane. The scenario considered transfer efficiency of virions on the banknote to fingertips when droplets were still wet and after having dried up and subsequently being touched by finger printing or rubbing the object. Accounting for the likelihood of the scenario to occur by considering (1) a local prevalence of 100 COVID-19 cases/100,000 persons, (2) a maximum of about one-fifth of infected persons transmit high virus loads, and (3) the numbers of cash transactions/person/day, the risk of contracting COVID-19 via person-to-person cash transactions was estimated to be much lower than once per 39,000 days (107 years) for a single person. In the general populace, there will be a maximum of 2.6 expected cases/100,000 persons/day. The risk for a cashier at an average point of sale was estimated to be much less than once per 430 working days (21 months). The depicted scenario is a rare event, therefore, for a single person, the risk of contracting COVID-19 via person-to-person cash transactions is very low. At a point of sale, the risk to the cashier proportionally increases but it is still low.

KEYWORDS

cash payment, cash transaction, coronavirus, COVID-19, fomite, QMRA, risk assessment, virus transmission

1 | INTRODUCTION

The current SARS-CoV-2 inflicted COVID 19 pandemic has triggered concerns globally based on general assumptions about transmission of the virus via the exchange of banknotes and coins (Auer et al., 2020; Central Banking, 2020a, 2020b; Gardner, 2020; Roh, 2020). This was linked to general fears that any frequently touched objects such as banknotes and coins have long been suspected to serve as a transmission vehicle (fomites) of various pathogenic bacteria, parasites, fungi, and viruses and now including SARS-CoV-2 (Angelakis et al., 2014; Galbadage et al., 2020; Pal & Bhadada, 2020). In the absence of evidence to the contrary, and

based on the relative importance of the four normal viral transmission routes (direct transmission by droplets and touch, indirect transmission via aerosols and fomites), a diligent precautionary approach was adopted and promoted by governments and public health authorities (CDC, 2019; WHO, 2020). On top of that, some central banks also issued statements that they were temporarily quarantining or disinfecting deposited banknotes before reissuing them, or even incinerating them (Choi, 2020; Schroeder & Irrera, 2020; Yeung, 2020). These types of statements undoubtedly had an impact on the means of payments citizens decided to use for their transactions. Indeed, survey data collected by the European Central Bank in July 2020 among the general

public showed that around 40% of the population of the euro area was to a certain degree concerned about the risk of being infected by handling cash. At the same time, it was seen that one of the main reasons for respondents changing their payment behavior was simply convenience, but it was also partially due to the general concern of being infected via the banknotes themselves, or via hand contact or close proximity to a cashier. It probably was also because of various governmental recommendations to pay online (ECB, 2020), which subsequently led to an increase in the use of other means of payment. Still, cash plays a very important role in society worldwide. As stated by the ECB (2020), it is in fact indispensable for a number of reasons, among which is the social inclusion of a substantial number of citizens with limited or no access to alternative forms of payment. It is therefore in the interests of society to properly assess the risk due to exposure to SARS-CoV-2 particles via cash as a fomite in payment transactions, and not make uninformed decisions.

The US Centers for Disease Control and Prevention (CDC) has recently published a “Science brief” on the possible transmission of SARS-CoV-2 from surfaces (CDC, 2021). Here, it is pointed out that the risk of fomite-mediated transmission is dependent on the infection prevalence rate in the community, the amount of virus that infected people expel, the deposition of expelled virus particles onto surfaces (fomites), the interaction with environmental factors, the time between surface contamination and a person touching the surface, the transfer efficiency of virus particles from fomite surfaces to hands and from hands to mucous membranes on the face (nose, mouth, eyes) and, lastly, the dose of virus needed to cause infection through the mucous membrane route. In this science brief, it is concluded that the risk of fomite transmission of SARS-CoV-2 is considered low compared with direct contact, droplet transmission, or airborne transmission, whilst referring to Kampf et al. (2020) and Meyerowitz et al. (2021). Also in this science brief, references to reports are given that indicate that SARS-CoV-2 is transmitted between people by touching surfaces that an ill person has recently coughed or sneezed upon, and then immediately touching their mouth, nose, or eyes (Harvey et al., 2020; Pitol & Julian, 2021; Wilson et al., 2021). “Other factors that may have influenced the risk assessment, such as frequency of contact with fomites, were not discussed in the science brief.”

Recently, Todt et al. (2021) examined the stability of SARS-CoV-2 on different means of payment and developed a touch transfer method to examine transfer efficiency from contaminated surfaces to fingertips. The transfer efficiencies as well as the persistence of the virus from Todt et al. (2021) indicated that the transmission of SARS-CoV-2 via contaminated coins and banknotes requires high viral loads and a timely order of specific events.

To understand this better, a quantitative microbial risk assessment (QMRA) was conducted to quantify the risks related to a scenario where an infectious person (provider) contaminated a banknote by coughing on it, and then immediately handed it over to a second person (acceptor). The acceptor was then possibly infected by transferring SARS-CoV-2

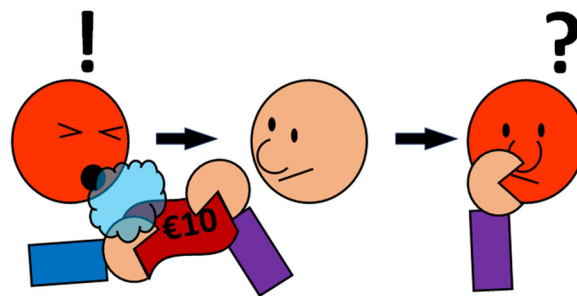


FIGURE 1 Schematic view of the contamination scenario

virions with their fingers from the contaminated banknote to a facial mucous membrane. The transfer data of Todt et al. (2021) was analyzed to pave the way to assess the risk of SARS-CoV-2 transmission by banknotes and coins, between two people. The risk assessment was focused on banknotes and not on coins, because it can be assumed that coins generate a lower risk compared to banknotes simply due to their much-reduced exposed surface areas.

2 | METHODS

2.1 | Scenario

The risk assessment comprised the following sequence of events thus defining a scenario as schematically depicted in Figure 1:

1. A highly infectious person holds a banknote to make a payment and coughs upon it. The cough generates a plume of respiratory droplets and droplet nuclei containing SARS-CoV-2 virions. Part of the plume contaminates the banknote with virions.
2. The infectious person then passes the banknote to another person (acceptor). Virions are transferred from the banknote to the fingers of the acceptor via touching the freshly contaminated banknote.
3. Virions are then transferred from the acceptor's fingers to their eyes, nose, or mouth by touching. This number of transferred virions is considered to be the dose.

Note that the assessment did not cover the many other likely permutations of the possible transfer route, that is, the possible intermediary role of wallets, cash machines, pockets, other precautionary measures such as face masks, hand cleaning, and the use of rubber gloves as these routes most probably would lead to a lower amount of virions transferred. During storage of cash in wallets, cash machines, and pockets, virus numbers will decrease significantly (Todt et al., 2021).

The risk characterization entailed the dose response relationship, expressing the risk per event as described in the exposure assessment, and a sensitivity analysis.

Because only short time frames were considered in this sequence of events, and SARS-CoV-2 has been observed

TABLE 1 Parameter values

	Unit	Distribution	Parameter values	Mean	5%	95%
$\text{Log}_{10}c$	$\text{Log}_{10}(\text{N/ml})$	Normal	$\mu = 7.5, \sigma = 1.3$	7.5	5.4	9.7
V	μl	Normal, $0-\infty$	$\mu = 8.4, \sigma = 7.0$	10	1.4	20
X	cm	Triangular	min = 20, max = 50, mode = 40	37	25	46
θ	°	Triangular	min = 20.5, max = 27.3, mode = 23.9	24	21	26
A	cm^2	Triangular	min = 1, max = 4, mode = 2	2.3	1.4	3.5
f_a	–	Equation 3	–	0.0025	0.0011	0.0050
$k_{1,\text{wet}}$	–	Beta	$\alpha = 1.5, \beta = 5.9$	0.20	0.026	0.45
$k_{1,\text{dry,print}}$	–	Beta	$\alpha = 2.3, \beta = 1000$	0.056	0.00071	0.19
$k_{1,\text{dry,rub}}$	–	Beta	$\alpha = 0.62, \beta = 11$	0.0024	0.00051	0.0053
k_2	–	–	0.34			
f_v	–	–	1/80			
R	–	–	1/18			

to remain infectious in aerosols and on banknotes for hours (Fears et al., 2020; Todt et al., 2021; van Doremalen et al., 2020), decay over time was not modeled in this study. Due to the drying of virus-containing droplets on a surface, virus inactivation proceeds initially faster as shown by Todt et al. (2021). But in a timeframe of seconds to a minute this does not play a role in this assessment and has not been taken into account. The lower transfer efficiencies under dry conditions may be due to picking up virions less efficiently in combination with the numbers of virions that were already reduced due to the drying.

This assessment concludes with an estimate of the likelihood of the depicted scenario while putting the risk assessment in perspective for the general risk per person per day, for both person-to-person and points-of-sale cash transactions.

2.2 | Risk assessment

2.2.1 | Virus concentration

It was assumed that the viral concentration C [virus RNA copies/ml] in droplets from a cough were the same as determined in throat and nasal swabs from infected persons. To this end, viral concentration data collected during the pandemic before July 2020 as published by Schijven et al. (2021) were used. Here, only the onset of symptoms when the concentrations are highest was considered. Table 1 lists the corresponding parameters.

2.2.2 | Total volume of droplets in a cough

Data on numbers and size distributions of expiratory droplets expelled during coughing were kindly provided by Chao et al. (2009), who measured droplet size using the interferometric Mie imaging. In that study, measurements were conducted at 1 cm in front of the mouth. Therefore, evaporation of

the droplets (which would decrease their volume and, hence, increase the concentration of virions in the droplets) was not considered. Because of the 20–50 cm distance between the mouth of the infectious person and his/her hand holding a banknote, the whole spectrum of expelled droplets as found by Chao et al. (2009) was considered. Chao et al. (2009) used a factor of 18.94 to obtain a mean total droplet count of 2085. Chao et al. (2009) kindly provided the original data from 10 healthy volunteers from which the variability in the measurements could be included in the risk assessment as follows: For each volunteer i , data were collected in 17 size bins of different diameters ranging from 1 to 2000 μm , that were converted to mean volumes $V_{i,j}$ (ml) per size bin j :

$$V_{i,j} = 10^{-12} \frac{\pi}{6} \left(d_{i,j,\text{min}}^3 + d_{i,j,\text{max}}^3 \right) / 2 \quad (1)$$

where d is the diameter (μm) and min and max designate minimum and maximum values per size bin, respectively.

The total volume of droplets from a cough per volunteer, V_i (ml) was calculated by summing $n_{i,j}$ samples of $V_{i,j}$ for each V_i :

$$V_i = \sum_{j=1}^{17} V_{i,j} n_{i,j} \quad (2)$$

Finally, a normal distribution that was truncated between zero and infinity was fitted to the 10 V_i values.

2.2.3 | Caught fraction of projected cough plume

It was assumed that at the moment of coughing, the infectious person held a banknote in their hand at a distance X from the face, and only a fraction of the cough plume directed to the banknote actually contaminated the banknote. Subsequently,

the exposed person accepted the banknote and touched part of its surface area with their fingertips where transfer of virions from the banknote to the fingertips could take place. The fraction of the projected cough plume on the banknote that is touched by the fingertips and thereby caught by the exposed person, f_a , was calculated as:

$$f_a = \frac{A}{\pi[(X + 4) \tan\theta]^2} \quad (3)$$

where A is the surface area (cm^2) of the fingertips touching the banknote, X is the distance (cm) between the mouth of the infectious person and the banknote at the time of coughing. Distance X was augmented by 4 cm to include the distance from the throat (the origin of the plume) to the mouth opening. θ is the opening angle of the cough plume (Bourouiba et al., 2014). A , X , and θ were all modeled as triangular distributions. See Table 1 for the corresponding distribution parameter values.

2.2.4 | Transfer efficiencies from banknote to hand

The transfer efficiency data of infectious SARS-CoV-2 virions from surfaces of banknotes and coins to artificial skin as reported by Todt et al. (2021) were analyzed in the current study by means of a multivariate linear regression for the relationship between the transfer efficiencies and the input concentrations, types of surfaces, and transfer methods and conditions. (Input concentrations and transfer efficiencies: log base 10; types of surfaces: €0,10 coin, €10 banknote, PVC, steel; transfer condition: wet = immediate contact after inoculation, dry = after desiccation of the droplet; transfer method: by finger print of finger rubbing; regression analyses: R (version 3.5.2 (2018-12-20) - "Eggshell Igloo") and lm (Chambers & Hastie, 1992; Wilkinson & Rogers, 1973)). Note that data for input concentrations less than 2320 infectious virions per ml were excluded from the analysis, because those values as well as the output concentrations (after transfer) were near or below the detection limit and did not allow to determine a transfer efficiency. The model with the lowest Akaike's information criterion (AIC) was selected using the step-function (parameter $k = 3.84$). For graphical presentation of the data package ggplot2 was used (Wickham et al., 2016). Transfer efficiencies were grouped along the significance of the effects of type of surface, transfer condition and method. For each group of transfer efficiencies, a Beta distribution was fitted and labelled $k_{1,\text{group}}$. Note that it was assumed that the transfer efficiencies from Todt et al. (2021) for infectious virions also applied to virus RNA copies.

The rate of hand contact with target facial membranes (mouth, eyes, nostrils) was estimated to be on average 15.7 per hour (Nicas & Best, 2008), that is, once every 4 min, and, therefore, frequent enough to justify almost immediate transfer to the facial membranes after having touched the contam-

TABLE 2 Parameter estimates from regression analysis of the \log_{10} of the transfer efficiencies

	Estimate	Standard error	Pr(> t)
Dry/wet: wet	1.0	0.17	3.5×10^{-7}
Print/rub: rub	-0.5	0.17	5.7×10^{-3}

Adjusted $R^2 = 47\%$; 45 degrees of freedom.

inated banknote. For transfer efficiency, k_2 , of SARS-CoV-2 from contaminated fingers to the face, that is, lips, nose, eyes, the value 0.34 for transfer of bacteriophage PRD1 was taken from Rusin et al. (2002). Bacteriophage PRD1 is an environmentally persistent virus, which is strongly negatively charged, and, therefore, can be considered as a conservative model virus regarding virus persistence and attachment to surfaces (Schijven & Hassanizadeh, 2000).

2.2.5 | Dose and risk

The dose D was computed as follows:

$$D \sim \text{Pois}(f_v k_1 k_2 f_a CV) \quad (4)$$

where $f_v = 1/80$ and is a conservative estimate of the fraction of intact virions that are able to infect specific cells in a tissue culture (Schijven et al., 2021).

Finally, the risk of contracting COVID-19, P_{ill} , was computed using the exponential dose response model:

$$P_{\text{ill}} = 1 - e^{-rD} \quad (5)$$

where r is the preliminary dose response parameter proposed by Haas (2021). Haas (2021) recommended to use the dose response data for human coronavirus 229E as representative for SARS-CoV-2. For human coronavirus 229E, it was found that each plaque forming unit (pfu) has a probability of $r = 1/18$ of causing illness symptoms.

2.2.6 | Fitting of distributions and Monte Carlo simulation

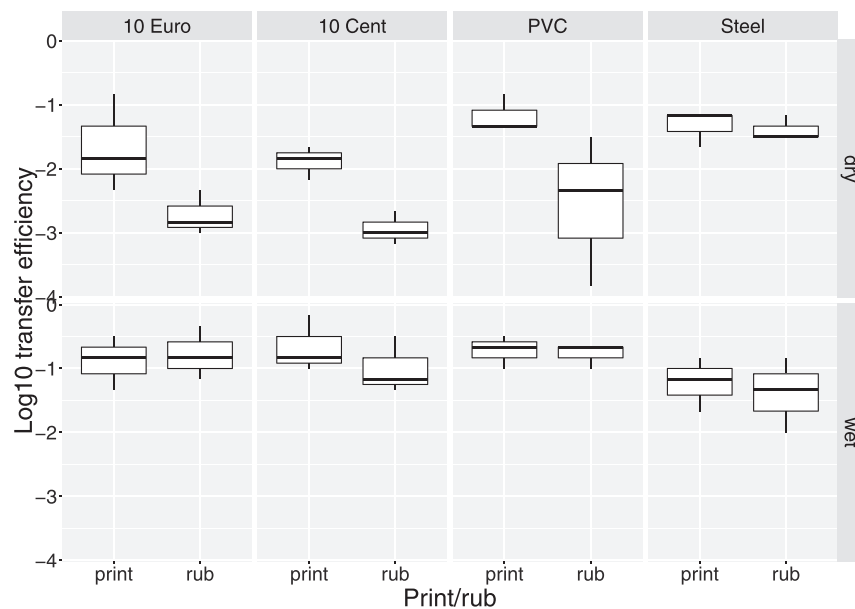
Fitting distributions to data of V and $k_{1,\text{group}}$ and drawing 10,000 Monte Carlo samples of C , V , A , X , θ , and $k_{1,\text{group}}$ were conducted in Mathematica (version 12.3.0.0, Wolfram Inc, Champaign, IL, USA).

3 | RESULTS

Table 3 lists the numbers of virus RNA copies present in a single cough ("coughed"), caught on a banknote area of a size covered by fingertips ("caught on fingertip area"), then actually transferred to the fingertips and, finally to a mucosal site of the facial area ("dose"). These numbers varied by many

TABLE 3 Numbers of virus RNA copies in the coughed plume, caught on fingertip area, transferred to fingertips and dose according wet, dry/print, and dry/rub scenarios

	Mean	Min	Max	Median	5%	95%
Coughed	2.5×10^7	2	2.0×10^{10}	2.5×10^5	1.6×10^3	4.3×10^7
Caught on fingertip area	6.2×10^4	0	4.3×10^7	5.6×10^2	3	1.0×10^5
Wet: transfer to fingertips	1.4×10^4	0	1.5×10^7	8.4×10^1	0	1.7×10^4
Wet: dose	4.7×10^3	0	5.1×10^6	2.9×10^1	0	5.8×10^3
Dry/print: transfer to fingertips	3.1×10^3	0	5.6×10^6	1.3×10^1	0	3.8×10^3
Dry/print: dose	1.0×10^3	0	1.9×10^6	5	0	1.3×10^3
Dry/rub: transfer to fingertips	1.5×10^2	0	1.4×10^5	1	0	2.0×10^2
Dry/rub: dose	5.0×10^1	0	4.8×10^4	0	0	6.9×10^1

**FIGURE 2** Boxplots of the \log_{10} transfer efficiency data according to the type of surface and transfer under wet and dry conditions by printing and rubbing. Data from Todt et al. (2021)

orders of magnitude, which stemmed from a combination of the large variation in virus concentration in patient material and the large variation in volume of coughed droplets. The numbers caught on the banknote on a fingertip-sized area were about 400 times lower than the numbers present in a single cough. Under wet conditions, the numbers transferred to the fingertips were lowered by about five times. Under dry conditions, the virus RNA copy numbers were reduced 20 and 400 times by printing and rubbing, respectively. The amount transferred from the fingertip to the facial area, the dose, was about one-third of the numbers on the fingertips. At the end, the dose was on average about 5000, 25,000, and 500,000 times lower than the numbers of coughed virions for the wet, dry/print, and dry/rub scenarios, respectively.

Figure 2 presents the boxplots of the transfer efficiency data according to the type of surface and transfer under wet and dry conditions by printing and rubbing, and shows that the transfer efficiencies under wet conditions were higher than under dry conditions. It can also be seen that under wet conditions, transfer efficiencies were similar for printing and rubbing, but that under dry conditions, transfer efficien-

cies were lower for rubbing than for printing. According to the statistical analyses of the transfer efficiency data, input concentration and the type of surface did not significantly affect transfer efficiency, but, dry/wet conditions and printing/rubbing did significantly affect transfer efficiency. Under wet conditions, transfer efficiencies were on average 10 times higher than under dry conditions and transfer efficiencies were on average three times lower for rubbing compared to printing (see estimated coefficients in Table 2). Therefore, for the risk assessment, the beta distributions were fitted to the transfer efficiencies k_1 of the €10 banknote under wet conditions, regardless of printing or rubbing and for the dry conditions accounting for printing and rubbing. The corresponding parameters of the three k_1 's are listed in Table 1.

Figures 3(A–C) depict the corresponding mean risks of 0.17 (= 1/6), 0.082 (= 1/12), and 0.014 (= 1/71) per cash transaction under the scenario, which is assuming an infectious person immediately handed over a heavily contaminated banknote followed by wet, dry/print and dry/rub transfer conditions, respectively. The risk distributions spanned the range from zero to one due to the wide ranges of the transferred

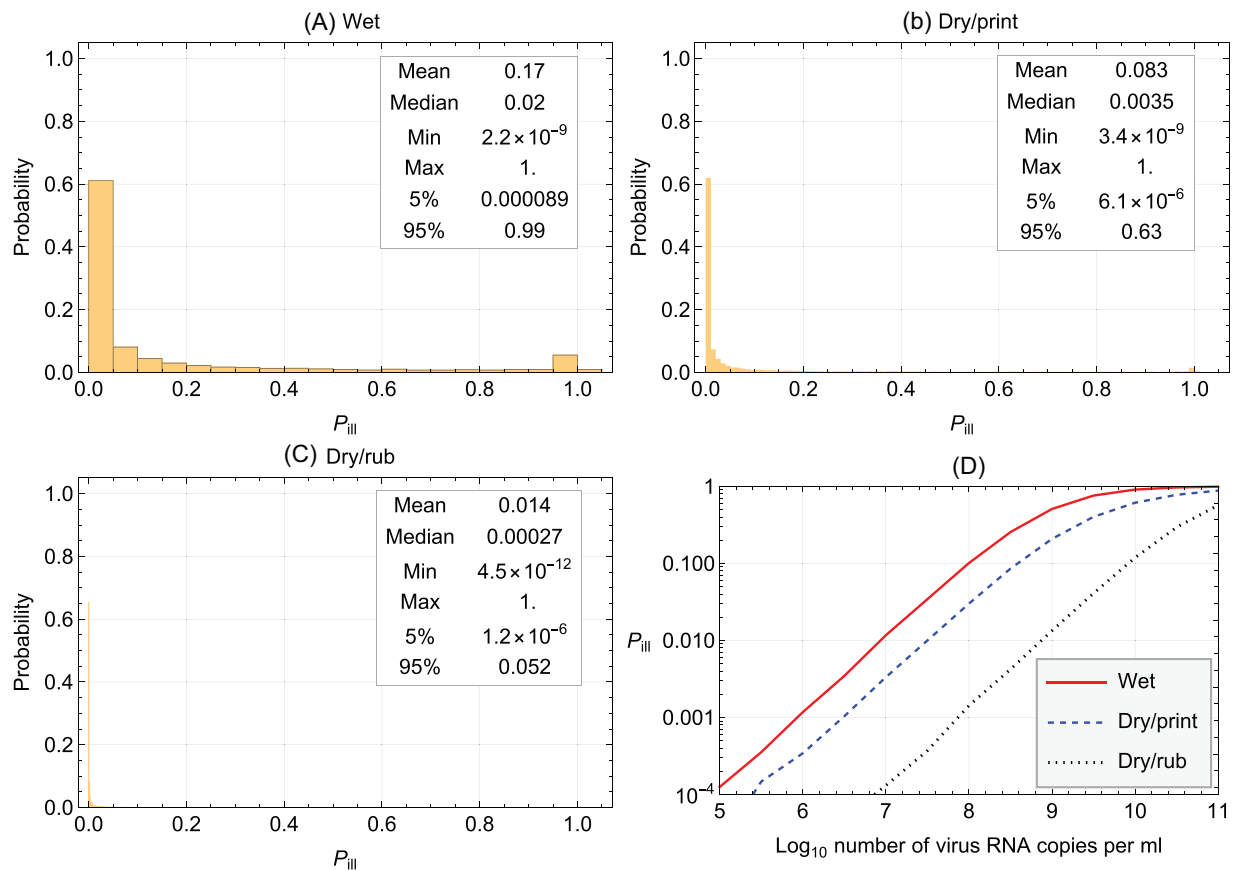


FIGURE 3 Histograms (A, B, C) of the distribution of the risk P_{ill} of contracting COVID-19 according to three transfer scenarios (wet, dry/print, and dry/rub transfer) and (D) the mean risk P_{ill} of contracting COVID-19 as a function of the number of virus RNA copies per ml mucus for each of the three transfer conditions in the depicted scenario. The probability that an infectious person at the onset of symptoms is expelling at least 10^5 , 10^6 , 10^7 , 10^8 , 10^9 , 10^{10} , or 10^{11} RNA copies/ml is 100, 88, 66, 36, 13, 2.7, and 0.34%, respectively, based on virus load data in the beginning of the pandemic

numbers of virus particles. These risk estimates can also be expressed as contracting on average COVID-19 once per 6, 12, and 71 cash transactions carried out under the scenario for the wet, the dry/print, and the dry/rub transfer conditions, respectively.

Figure 3(D) depicts the mean risk P_{ill} of contracting COVID-19, as a function of a given number of virus RNA copies per milliliter mucus for each of the three transfer scenarios over the concentration range from 10^7 to 10^{11} virus RNA copies per ml. In the legend, the corresponding percentiles are given for having at least a specific virus concentration. From these curves, it can be seen that the risk level of 1% will be exceeded at a virus concentration of about 10^7 , 6×10^7 and 10^9 virus RNA copies per ml for the wet, dry/print, and dry/rub transfer scenarios, respectively. The risk level of 10% will be exceeded at a virus concentration of about 10^8 , 6×10^8 , and 10^{10} virus RNA copies per ml for the wet, dry/print, and dry/rub transfer scenarios, respectively. In summary, under the scenario, in which an infectious person immediately handed over a contaminated banknote, these curves imply that in the wet transfer scenario, with an about average virus concentration of 10^8 virus RNA copies per ml, the risk can be considered high, which is no surprise given the conditions. But in the dry/rub

scenario, a high virus concentration as produced by a super spreader expelling virus at a concentration of 10^{10} virus RNA copies per ml would be required to achieve the same risk level.

4 | DISCUSSION

The current study aimed to assess, using a number of assumptions, the risk of becoming ill through using cash in a transaction with another person, which acts as a fomite of SARS-CoV2 during cash payment transactions. A coughing scenario was selected, because a cough expels the large numbers of droplets and aerosols, and hence, large numbers of viruses (Schijven et al., 2021). Coughing directly in the hand, which then takes a banknote and contaminate it, may also lead to a high contamination level, however this is another transfer step extra, and, moreover, when coughing or sneezing it was advised to use the elbow.

Note that 1 PFU corresponded to a conservative estimate of one per 80 virus RNA copies (Schijven et al., 2021). The latter in combination with the prudent preliminary dose response parameter of 1/18 (Haas et al., 2021), corresponded to 1/1440 virus RNA copies on average leading to illness,

which was not too conservative after all because it matched the number of viral genomes needed to initiate infection of about 1000 (1–5000) as reported by Popa et al. (2020) based on a transmission network with 39 transmission events. Basu (2021) estimated an infectious dose of about 100 virions to explain a superspreading event.

To determine the volume of droplets in a single cough using the data from Chao et al. (2009) variability in numbers of coughed droplets between persons was accounted for. Jones (2020) also used the Chao data but accounting for variability by using Poisson variance for each diameter class, which is a much narrower distribution. In contrast, Duguid (1945) reported much wider ranges of expelled particles of 1–100 μm by a lip cough of 490–16,000 or a tongue-teeth cough of 1500–52,000.

According to the statistical analysis of the transfer efficiency data, the type of surface was apparently an insignificant factor, nevertheless, risk estimates for a scenario in which a €1 or €2 coin was handed over should be lower simply because the fingertips of the payer shield most of the coin surface area against virus contamination from a cough.

The risk assessment demonstrated that risks of contracting COVID-19 could be high in the events as described. Transfer efficiencies were derived from the experimental data from Todt et al. (2021), in which droplet spots of 10 μl (diameter of about 5 mm) were deposited on the different surfaces. Desiccation has been shown to reduce the numbers of virions by two orders of magnitude after 7 h (Todt et al., 2021). In the contamination event, the amount of mucus caught on the banknote is likely dispersed over much smaller droplets, and, hence, desiccation may happen much faster. Therefore, it can be deduced that later repeated contact with the fomites on bank notes that ended in a wallet or cash register, directly after the contamination, is not relevant.

From Equation 4, it is obvious that dose D is directly proportional to the concentration of virus RNA copies C , the volume of droplets in a single cough V , the fraction of the cough caught by the area covered by fingertips f_a , the transfer efficiencies k_1 and k_2 , and, finally, the fraction of infectious viruses f_v . Table 1 shows that the 5-percentile to 95-percentile range of the concentration of virus RNA copies C spanned four orders of magnitude, but one order for all the other parameters. Therefore, the variability in dose D is by far determined by the concentration of virus RNA copies C . Figure 3(D) depicts the mean risk P_{ill} of contracting COVID-19 as a function of the number of virus RNA copies per ml mucus for each the three transfer scenarios over the concentration range from 10^7 to 10^{11} virus RNA copies per ml. Considering 10^{10} virus RNA copies per ml representing a super spreader event (Schijven et al., 2021), values of the mean risk P_{ill} become high for all three transfer scenarios. The viral load of the Delta variant might be at this level because there are indications that the viral load of the Delta variant is 1000 times higher than the initial variants of 2020 (Li et al., 2021) but the sample size of this study was limited. Comparing the viral load in 16,185 samples, von Wintersdorff et al. (2021) found that the Delta variant contained about four-

fold higher viral loads compared to the non-VOC or Alpha variants.

The virus transmission route that was chosen, that is, coughing onto a banknote and then immediately passing it to another person by hand, can be assumed to happen only very rarely in public life because it is neither socially acceptable nor courteous, and people would normally avoid such an action. During the pandemic, it probably became even less likely due to hygienic measures, social distancing, wearing of masks, and increased awareness. Evaluation of the likelihood of the depicted event entails analyzing the frequency of cash transactions, prevalence of SARS-CoV-2 infection, as well as physical/biological susceptibility to SARS-CoV-2 infection. According to a study on the payment attitudes of consumers in the euro area in 2019, 1.2×10^{11} cash transactions (1.1×10^{11} point-of-sale and 8.0×10^9 person-to-person) were made involving a value of $\text{€}2.0 \times 10^{12}$ (ECB, 2020). This amounts to an average of €17 per cash transactions and may be interpreted that at least one banknote is involved in each cash transaction. The same study estimated that on average in the euro area, consumers made 1.1 cash transactions and 0.4 card transactions per person per day, and also that banknotes are used in 70% of the cash payments (ECB, 2020).

As previously stated, in the depicted event, the risk of contracting COVID-19 under wet transfer conditions from a banknote was estimated to be one per six events. In reality, not every infectious person is at the onset of symptoms when emission of virions is at its highest. About 10–20% of people with COVID-19 cause 80% of subsequent infections—which may lead to so-called superspreading events—while 60–75% of people with COVID-19 infect no one else (Bi et al., 2020; Chen et al., 2021; Endo et al., 2020; Goyal et al., 2021). Most people with COVID-19 infect no one because they expel little—if any—infectious SARS-CoV-2 when they talk, breathe, sing, or cough, but highly infectious individuals on the other hand have high concentrations of the virus in their airways, particularly the first few days after developing symptoms, and can expel tens to thousands of infectious virus particles per minute (Chen et al., 2021). Interpreting this heterogeneity in transmissibility and shedding of SARS-CoV-2, in which at maximum about one fifth of infected persons transmit high loads of virus particles, it may be assumed that estimated risks are at least five times lower than those estimated for the scenario with a person at the onset of having symptoms. Taking a local prevalence of SARS-CoV-2 cases of 100 per 100,000 persons as anchor point (ECDC, 2022), together with the knowledge that there are 1.1 cash transactions per person per day, this would imply that a person-to-person cash transaction with an infectious person would occur with a probability of 1.1/1000 per day. For a single person, this leads to a risk estimate of contamination of once per $5 \times 1000 / (0.17 \times 1.1 \times 0.7) = 39,000$ days (107 years) for person-to-person cash transactions.

Also, hardly any person will cough on a banknote when paying, therefore, this risk estimate must actually be much lower than once per 39,000 days for the average citizen. How

much lower the risk is due to this is unknown. Additionally, when taking into account that currently in European countries a substantial part of the population has now acquired immunity by infection or vaccination, this risk can now be proportionally lowered even further as time progresses. A second conclusion is that in the general populace, assuming 100 infectious persons per 100,000, there will be much less than $100,000 \times 1/5 \times 0.17 \times 1.1 \times 0.7/1000 = 2.6$ expected cases per 110,000 transactions (100,000 persons) per day.

Point-of-sale and person-to-person cash transactions differ significantly in frequency and exposure levels and therefore should be considered separately. At any point of sale, a cashier at a supermarket or similar shop may be dealing with cash transactions many more times per day, and is therefore, more exposed to the risk of touching contaminated banknotes and objects. At an average point of sale, with a cashier conducting 100 cash transactions per day, the risk for the cashier with no protection is obviously proportionally increased compared to the risk per single person-to-person cash transactions to a rate much lower than once per $(39,000 \times 1.1/100 =)$ 430 working days (21 months). This again emphasizes that it is important that adequate precautions are taken at points of sale to protect the cashier. Having an infectious cashier must obviously be avoided at all times, emphasizing the importance of the public messages for regular testing and that every person with symptoms must self-isolate.

To conclude, the overall risk of transmission via banknotes between members of the general public with no protection is very low (much less than once every 39,000 days). The scenario as analyzed in this paper may be a high-risk event, but it is also a rare event. Obviously, cashiers are more at risk than the public (much less than once every 430 days) even if still with a low risk to contract COVID-19 through exposure to SARS-CoV-2 via cash. In any case, this should not prevent from following the national and international guidelines in such circumstances. These low risks support that fomite transmission should be regarded as no more than a very minor component of this pandemic as pointed out by Goldman (2021), who also concludes that normal routine hygiene is all that is needed.

Note that the risk outcomes were based on 100 cases/100,000 persons. In January 2022, in many areas in Europe, 500 cases per 100,000 persons were exceeded. Multiplying the risk estimates in this study by a factor of ten still result in low values. Note that in that situation, transmissions via other pathways have increased also (ECDC, 2022). Additional research remains necessary to assess if the risk increases significantly because of potentially newer virus variants.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

- Angelakis, E., Azhar, E. I., Bibi, F., Yasir, M., Al-Ghamdi, A. K., Ashshi, A. M., Elshemi, A. G., & Raoult, D. (2014). Paper money and coins as potential vectors of transmissible disease. *Future Microbiology*, 9(2), 249–261.
- Auer, R., Cornelli, G., & Frost, J. (2020). Covid-19, cash, and the future of payments (No. 3). Bank for International Settlements.
- Basu, S. (2021). Computational characterization of inhaled droplet transport to the nasopharynx. *Scientific Reports*, 11(1), 1–13.
- Bi, Q., Wu, Y., Mei, S., Ye, C., Zou, X., Zhang, Z., Liu, X., Wei, L., Truelove, S. A., Zhang, T., Gao, W., Cheng, C., Tang, X., Wu, X., Wu, Y., Sun, B., Huang, S., Sun, Y., Zhang, J., ... Feng, T. (2020). Epidemiology and transmission of COVID-19 in 391 cases and 1286 of their close contacts in Shenzhen, China: A retrospective cohort study. *The Lancet Infectious Diseases*, 20, 911–919. [https://doi.org/10.1016/S1473-3099\(20\)30287-5](https://doi.org/10.1016/S1473-3099(20)30287-5), PMID: 32353347
- Bourouiba, L., Dehandschoewercker, E., & Bush, J. W. M. (2014). Violent expiratory events: On coughing and sneezing. *Journal of Fluid Mechanics*, 745, 537–563.
- CDC Science Brief. (2021). *SARS-CoV-2 and surface (fomite) transmission for indoor community environments*. Centers for Disease Control and Prevention, 5 April 2021. <https://www.cdc.gov/coronavirus/2019-ncov/more/science-and-research/surface-transmission.html>
- CDC. (2019). *How COVID-19 spreads*. Centers for Disease Control and Prevention. <https://www.cdc.gov/coronavirus/2019-ncov/prepare/transmission.html>
- Central Banking. (2020a). *Covid-19 may survive 28 days on banknotes and payment cards*. <https://www.centralbanking.com/central-banks/currency/banknotes/7697391/covid-19-may-survive-28-days-on-banknotes-and-payment-cards>
- Central Banking. (2020b). *Will cash survive COVID-19?* <https://www.centralbanking.com/central-banks/currency/7509046/will-cash-survive-covid-19>
- Chambers, J. M., & Hastie, T. J. (1992). Linear models. In J. M. Chambers & T. J. Hastie (Eds.), *Statistical models in S* (p. 608). Wadsworth & Brooks/Cole.
- Chao, C. Y. H., Wan, M. P., Morawska, L., Johnson, G. R., Ristovski, Z. D., Hargreaves, M., Mengersen, K., Corbett, S., Li, Y., Xie, X., & Katosheviski, D. (2009). Characterization of expiration air jets and droplet size distributions immediately at the mouth opening. *Journal of Aerosol Science*, 40, 122–133.
- Chen, P. Z., Bobrovitz, N., Premji, Z., Koopmans, M., Fisman, D. N., & Gu, F. X. (2021). Heterogeneity in transmissibility and shedding SARS-CoV-2 via droplets and aerosols. *Elife*, 10, e65774.
- Choi, H. (2020, March 06). S. Korea's central bank burns, quarantines cash in coronavirus precaution. *Reuters*. <https://www.reuters.com/article/health-coronavirus-southkorea-money-idUSL4N2AZ1TL>
- Duguid, J. P. (1945). The numbers and the sites of origin of the droplets expelled during expiratory activities. *Scottish Medical Journal*, 52, 385–401.
- ECB. (2020). *Study on the payment attitudes of consumers in the euro area*. Space report. European Central Bank. <https://www.ecb.europa.eu/pub/pdf/other/ecb.spacereport202012~bb2038bbb6.en.pdf>
- ECDC. (2022). *Maps in support of the Council Recommendation on a coordinated approach to travel measures in the EU*. <https://www.ecdc.europa.eu/en/covid-19/situation-updates/weekly-maps-coordinated-restriction-free-movement>
- Endo, A., Abbott, S., Kucharski, A. J., & Funk, S. (2020). Centre for the mathematical modelling of infectious diseases COVID-19 working group. 2020. Estimating the overdispersion in COVID-19 transmission

- using outbreak sizes outside China. *Wellcome Open Research*, 5, 67. <https://doi.org/10.12688/wellcomeopenres.15842.3>, PMID: 32685698ss
- Fears, A. C., Klimstra, W. B., Duprex, P., Hartman, A., Weaver, S. C., Plante, K. S., Aguilar, P. V., Fernández, D., Nalca, A., Tatura, A., Dyer, D., Kearney, B., Lackemeyer, M., Bohannon, J. K., Johnson, R., Garry, R. F., Reed, D. S., & Roy, C. J. (2020). Comparative dynamic aerosol efficiencies of three emergent coronaviruses and the unusual persistence of sars-cov-2 in aerosol suspensions. medRxiv, 2020.2004.2013.20063784. <https://doi.org/10.1101/2020.04.13.20063784>
- Galbadage, T., Peterson, B. M., & Gunasekera, R. S. (2020). Does COVID-19 spread through droplets alone? *Frontiers in Public Health*, 8, 163.
- Gardner, B. (2020). Dirty banknotes may be spreading the coronavirus, WHO suggests. Daily Telegraph. <https://www.telegraph.co.uk/news/2020/03/02/exclusive-dirty-banknotes-may-spreading-coronavirus-world-health/>
- Goldman, E. (2021). SARS Wars: The fomites strike back. *Applied and Environmental Microbiology*, 87(13), e0065321.
- Goyal, A., Reeves, D. B., Cardozo-Ojeda, E. F., Schiffer, J. T., & Mayer, B. T. (2021). Viral load and contact heterogeneity predict SARS-CoV-2 transmission and super-spreading events. *Elife*, 10, e63537.
- Haas, C. N. (2021). Action Levels for SARS-CoV-2 in Air: Preliminary Approach. *Risk Analysis*, 41(5), 705–709.
- Harvey, A. P., Fuhrmeister, E. R., Cantrell, M. E., Pitol, A. K., Swarouth, J. M., Powers, J. E., Nadimpalli, M. L., Julian, T. R., & Pickering, A. J. (2020). Longitudinal monitoring of SARS-CoV-2 RNA on high-touch surfaces in a community setting. *Environmental Science & Technology Letters*, 8(2), 168–175.
- Jones, R. M. (2020). Relative contributions of transmission routes for COVID-19 among healthcare personnel providing patient care. *Journal of Occupational and Environmental Hygiene*, 17(9), 408–415.
- Kampf, G., Brüggemann, Y., Kaba, H. E. J., Steinmann, J., Pfaender, S., Scheithauer, S., & Steinmann, E. (2020). Potential sources, modes of transmission and effectiveness of prevention measures against SARS-CoV-2. *Journal of Hospital Infection*, 106(4), 678–697.
- Li, B., Deng, A., Li, K., Hu, Y., Li, Z., Shi, Y., Xiong, Q., Liu, Z., Guo, Q., Zou, L., Zhang, H., Zhang, M., Ouyang, F., Su, J., Su, W., Xu, J., Lin, H., Sun, J., Peng, J., ... Lu, J. (2021). Viral infection and transmission in a large well-traced outbreak caused by the Delta SARS-CoV-2 variant. medRxiv. <https://doi.org/10.1101/2021.07.07.21260122>
- Meyerowitz, E. A., Richterman, A., Gandhi, R. T., & Sax, P. E. (2021). Transmission of SARS-CoV-2: A review of viral, host, and environmental factors. *Annals of Internal Medicine*, 174(1), 69–79.
- Nicas, M., & Best, D. (2008). A study quantifying the hand-to-face contact rate and its potential application to predicting respiratory tract infection. *Journal of Occupational and Environmental Hygiene*, 5(6), 347–352.
- Pal, R., & Bhadada, S. K. (2020). Cash, currency and COVID-19. *Postgraduate Medical Journal*, 96(1137), 427–428.
- Pitol, A. K., & Julian, T. R. (2021). Community transmission of SARS-CoV-2 by surfaces: Risks and risk reduction strategies. *Environmental Science & Technology Letters*, 8(3), 263–269.
- Popa, A., Genger, J. W., Nicholson, M. D., Penz, T., Schmid, D., Aberle, S. W., Agerer, B., Lercher, A., Endler, L., Colaço, H., Smyth, M., Schuster, M., Grau, M. L., Martínez-Jiménez, F., Pich, O., Borena, W., Pawelka, E., Keszei, Z., Senekowitsch, M., ... Bergthaler, A. (2020). Genomic epidemiology of superspreading events in Austria reveals mutational dynamics and transmission properties of sars-cov-2. *Science Translational Medicine*, 12(573), eabe2555.
- Roh, J. (2020). Surge in damaged cash as worried South Koreans try to microwave the virus. Reuters. <https://www.reuters.com/article/us-health-coronavirus-southkorea-money-idUSKCN24W1SU>
- Rusin, P., Maxwell, S., & Gerba, C. (2002). Comparative surface-to-hand and fingertip-to-mouth transfer efficiency of gram-positive bacteria, gram-negative bacteria, and phage. *Journal of Applied Microbiology*, 93(4), 585–592.
- Schijven, J. F., & Hassanizadeh, S. M. (2000). Removal of viruses by soil passage: Overview of modeling, processes, and parameters. *Critical reviews in Environmental Science and Technology*, 30(1), 49–127.
- Schijven, J., Vermeulen, L. C., Swart, A., Meijer, A., Duizer, E., & deRoda Husma, N. A. M. (2021). Quantitative microbial risk assessment for airborne transmission of SARS-CoV-2 via breathing, speaking, singing, coughing, and sneezing. *Environmental Health Perspectives*, 129(4), 047002.
- Schroeder, P., & Irrera, A. (2020, March 06). Fed quarantines U.S. dollars repatriated from Asia on coronavirus caution. Reuters. <https://www.reuters.com/article/us-health-coronavirus-fed-dollars-idUSKBN20T1YT>
- Todt, D., Meister, T. L., Tamele, B., Howes, J., Paulmann, D., Becker, B., Brill, F. H., Wind, M., Schijven, J., Heinen, N., Kinast, V., Mhlekude, B., Goffinet, C., Krawczyk, A., Steinmann, J., Pfaender, S., Brüggemann, Y., & Steinmann, E. (2021). A realistic transfer method reveals low risk of SARS-CoV-2 transmission via contaminated euro coins and banknotes. *iScience*, 24(8), 102908.
- Van Doremalen, N., Bushmaker, T., Morris, D. H., Holbrook, M. G., Gamble, A., Williamson, B. N., Tamin, A., Harcourt, J. L., Thornburg, N. J., Gerber, S. I., Lloyd-Smith, J. O., de Wit, E., & Munster, V. J. (2020). Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *New England Journal of Medicine*, 382(16), 1564–1567.
- von Wintersdorff, C., Dingemans, J., van Alphen, L., Wolffs, P., van der Veer, B., Hoebe, C., & Savelkoul, P. (2021). Infections caused by the Delta variant (B.1.617.2) of SARS-CoV-2 are associated with increased viral loads compared to infections with the Alpha variant (B.1.1.7) or non-variants of concern. <https://doi.org/10.21203/rs.3.rs-777577/v1>
- WHO. (2020). *Modes of transmission of virus causing COVID-19: Implications for IPC precaution recommendations*. WHO reference number WHO/2019-nCoV/Sci_Brief/Transmission_modes/2020.2. <https://www.who.int/publications/i/item/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations>; https://apps.who.int/iris/bitstream/handle/10665/331616/WHO-2019-nCoV-Sci_Brief-Transmission_modes-2020.2-eng.pdf?sequence=1&isAllowed=y
- Wickham, H., Chang, W., & Wickham, M. H. (2016). Package ‘ggplot2’. Create elegant data visualisations using the grammar of graphics. *Version*, 2(1), 1–189. Wilkinson and Rogers, 1973.
- Wilkinson, G. N., & Rogers, C. E. (1973). Symbolic description of factorial models for analysis of variance. *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, 22(3), 392–399.
- Wilson, A. M., Weir, M. H., Bloomfield, S. F., Scott, E. A., & Reynolds, K. A. (2021). Modeling COVID-19 infection risks for a single hand-to-fomite scenario and potential risk reductions offered by surface disinfection. *American Journal of Infection Control*, 49(6), 846–848.
- Yeung, K. (2020, February 16). China central bank branch to destroy banknotes from coronavirus-hit sectors. *South China Morning Post*. <https://www.scmp.com/economy/china-economy/article/3050868/fresh-cash-old-china-central-bank-branch-destroy-banknotes>

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