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Comparative efficacy evaluation of disinfectants against severe acute respiratory syndrome coronavirus-2

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SUMMARY

Background: Disinfection is one of the most effective ways to block the rapid transmission of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2). Due to the prolonged coronavirus disease 2019 (COVID-19) pandemic, disinfectants have become crucial to prevent person-to-person transmission and decontaminate hands, clothes, facilities and equipment. However, there is a lack of accurate information on the virucidal activity of commercial disinfectants.

Aim: To evaluate the virucidal efficacy of 72 commercially available disinfectants constituting 16 types of ingredients against SARS-CoV-2.

Methods: SARS-CoV-2 was tested with various concentrations of disinfectants at indicated exposure time points as recommended by the manufacturers. The 50% tissue culture infectious dose assay was used to calculate virus titre, and trypan blue staining and CCK-8 were used to assess cell viability after 3–5 days of SARS-CoV-2 infection.

Findings: This study found that disinfectants based on 83% ethanol, 60% propanol/ethanol, 0.00108–0.0011% sodium dichloroisocyanurate and 0.497% potassium peroxymonosulfate inactivated SARS-CoV-2 effectively and safely. Although disinfectants based on 0.05–0.4% benzalkonium chloride (BAC), 0.02–0.07% quaternary ammonium compound (QAC; 1:1), 0.4% BAC/didecyldimethylammonium chloride (DDAC), 0.28% benzethonium chloride concentrate/2-propanol, 0.0205–0.14% DDAC/polyhexamethylene biguanide hydrochloride (PHMB) and 0.5% hydrogen peroxide inactivated SARS-CoV-2 effectively, they exhibited cytotoxicity. Conversely, disinfectants based on 0.04–4% QAC (2:3), 0.00625% BAC/DDAC/PHMB, and 0.0205–0.14% and 0.0173% peracetic acid showed approximately 50% virucidal efficacy with no cytotoxicity. Citric acid (0.4%) did not inactivate SARS-CoV-2.

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Conclusion: These results indicate that most commercially available disinfectants exert a disinfectant effect against SARS-CoV-2. However, re-evaluation of the effective concentration and exposure time of certain disinfectants is needed, especially citric acid and peracetic acid.

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Introduction

Coronavirus disease 2019 (COVID-19) is caused by severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) [1]. The major symptoms of COVID-19 are fever, shortness of breath, coughing and atypical pneumonia within 2 weeks of transmission [2—7]. The World Health Organization (WHO) declared the SARS-CoV-2 outbreak a global pandemic on 11 March 2020, and it is still affected the public health community worldwide [8]. SARS-CoV-2 is transmitted directly through droplets and indirectly via contaminated surfaces [9—12]. Previous studies have shown that SARS-CoV-2 remains viable in aerosols for up to 3 h, and can survive for >3 days on wood, metal, glass, plastic, paper and clothes [13—15]. The persistence of SARS-CoV-2 on contaminated surfaces is one possible means of transmission, meaning that the use of disinfectants to inactivate SARS-CoV-2 on surfaces is a key control measure [15]. Chemical disinfectants including alcohol, peroxide, aldehyde and quaternary ammonium compounds (QACs) have been developed to inactivate or eliminate viruses and bacteria. Previous reports showed that disinfectants based on 70% ethanol or isopropanol are highly effective against coronaviruses. Furthermore, 80% ethanol combined with a 5% isopropanol mixture rapidly inactivates human immunodeficiency virus, hepatitis B virus and hepatitis C virus [16,17]. Several studies demonstrated that 62—71% ethanol, 0.5% hydrogen peroxide and 0.1% sodium hypochlorite could inactivate human coronaviruses effectively on contaminated inanimate surfaces [18,19]. Moreover, disinfectants comprising acids or alkalis, such as citric acid and sodium carbonate, could inactivate several viruses [20,21]. However, chemical disinfectants have certain drawbacks, such as being required at a high concentration for complete inactivation of viruses, and causing harm to public health and the environment [22]. This study evaluated the virucidal activity of commercially available disinfectants composed of different active ingredients against SARS-CoV-2, and presented guidelines for the use of appropriate disinfectants.

Methods

Viruses and cells

African green monkey kidney epithelial (Vero E6) cells were cultured in Dulbecco's modified Eagle medium (DMEM) (GIBCO, Grand Island, NY, USA) supplemented with 10% fetal bovine serum (FBS, Gibco), 100 U/mL penicillin and 100 μg/mL streptomycin (Gibco). SARS-CoV-2 (BetaCoV/Korea/KCDC03/2020, NCCP43326) was received from Korea Disease Control and Prevention Agency. The titration of SARS-CoV-2 in Vero E6 cells was calculated by 50% tissue culture infectious dose ($TCID_{50}$) assay using the Reed—Muench method, as described previously [23]. Briefly, Vero E6 cells were infected with a dose of SARS-CoV-2 (100 $TCID_{50}$), and after 3—5 days of infection, the cytopathic effect was monitored by observing the morphological changes under a microscope (Leica Microsystems, Wetzlar, Germany). All SARS-CoV-2 infection-related experiments were conducted in a biosafety level 3 laboratory using personal protective equipment, according to the biosafety protocol of Korea Research Institute of Jeonbuk National University.

Chemical disinfectants

Seventy-two disinfectants were tested for virucidal activity against SARS-CoV-2 under the conditions recommended by the manufacturers, including working concentrations and exposure times (Table I and Table S1, see online supplementary material). Five types of wipes and 20 types of sprays, including ethanol, propanol and benzalkonium chloride (BAC) compounds, were tested without dilution. In total, two types of tablets, including sodium dichloroisocyanurate, two powders, including potassium peroxymonosulfate, and 43 liquids, including peracetic acid, hydrogen peroxide, citric acid, ethanol, propanol, BAC compounds and QACs, were diluted in ultrapure deionized water (Biosolution, Seoul, South Korea) and tested. The disinfectant effectiveness of QAC (1:1), sodium hypochlorite, ethanol and citric acid against SARS-CoV-2 was evaluated in organic and inorganic solutions. The inorganic solution contained 0.305 g of $CaCl_2$ and 0.139 g of $MgCl_2 \bullet 6H_2O$ in 1 l of distilled water, and the organic solution contained 5% FBS in the inorganic solution.

SARS-CoV-2 susceptibility against the disinfectants

The disinfectants were diluted in ultrapure water and mixed with SARS-CoV-2 according to the product recommendations (Table S1, see online supplementary material). The mixtures were incubated for 3—15 min depending on the product, and neutralized with DMEM containing 10% FBS [24—31]. Next, the mixtures were serially diluted to 10^{-1}—10^{-7} with serum-free DMEM and added to Vero E6 cells (2×10^4 cells/well). After 1 h of treatment, the mixture was removed from the cells and washed twice with serum-free (DMEM) (GIBCO, Grand Island, NY, USA) and DMEM containing 2% FBS filled in each well. The SARS-CoV-2 titre was calculated by the Reed-Muench method based on the cell death at 3-5 days post-infection. The percentage of SARS-CoV-2 reduction rate was quantified by the SARS-CoV-2 infectivity with disinfectants/without disinfectants, and the percentage variance was calculated by the standard deviation (SD).

Table I

Efficacies of commercial surface disinfectants including various active ingredients against severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2)

Number of product	Ingredient	Stock concentration (%)	Working concentration (%)	Exposure time (min)	SARS-CoV-2 reduction rate (%)
19	BAC	0.05–20	0.05–0.4	5–10	90.6667–100 ± 6.59966
32	Quaternary ammonium compound (1:1)	0.07–4.5	0.02–0.07	10	100
3	Quaternary ammonium compound (2:3)	0.04–4	0.04–4	10	53.09–58.33 ± 0.0488
1	BAC/DDAC	0.4	0.4	10	100
1	BAC/DDAC/PHMB	1.25	0.00625	10	54.5455
2	Benzethonium chloride concentrate/2-propanol	0.28	0.28	3–10	100
2	DDAC/PHMB	0.14–8.2	0.0205–0.14	5–10	30-100 ± 0.7615
2	Sodium dichloroisocyanurate	1.08–1.1	0.00108–0.0011	15	100
3	Ethanol	83	83	10	100
1	Propanol/ethanol	60	60	10	100
1	Hydrogen peroxide	0.5	0.5	10	100
2	Peracetic acid	1.73	0.0173	10	6.8–56.2852 ± 1
2	Potassium peroxymonosulfate	49.7	0.497	10	100
1	Citric acid	40	0.4	10	0

BAC, benzalkonium chloride; DDAC, didecyldimethylamonium chloride; PHMB, polyhexamethylene biguanide hydrochloride; quaternary ammonium compound, 80% N-alkyldimethylethylbenzylammonium chloride:alkyldimethylbenzylammonium chloride (1:1 or 2:3).

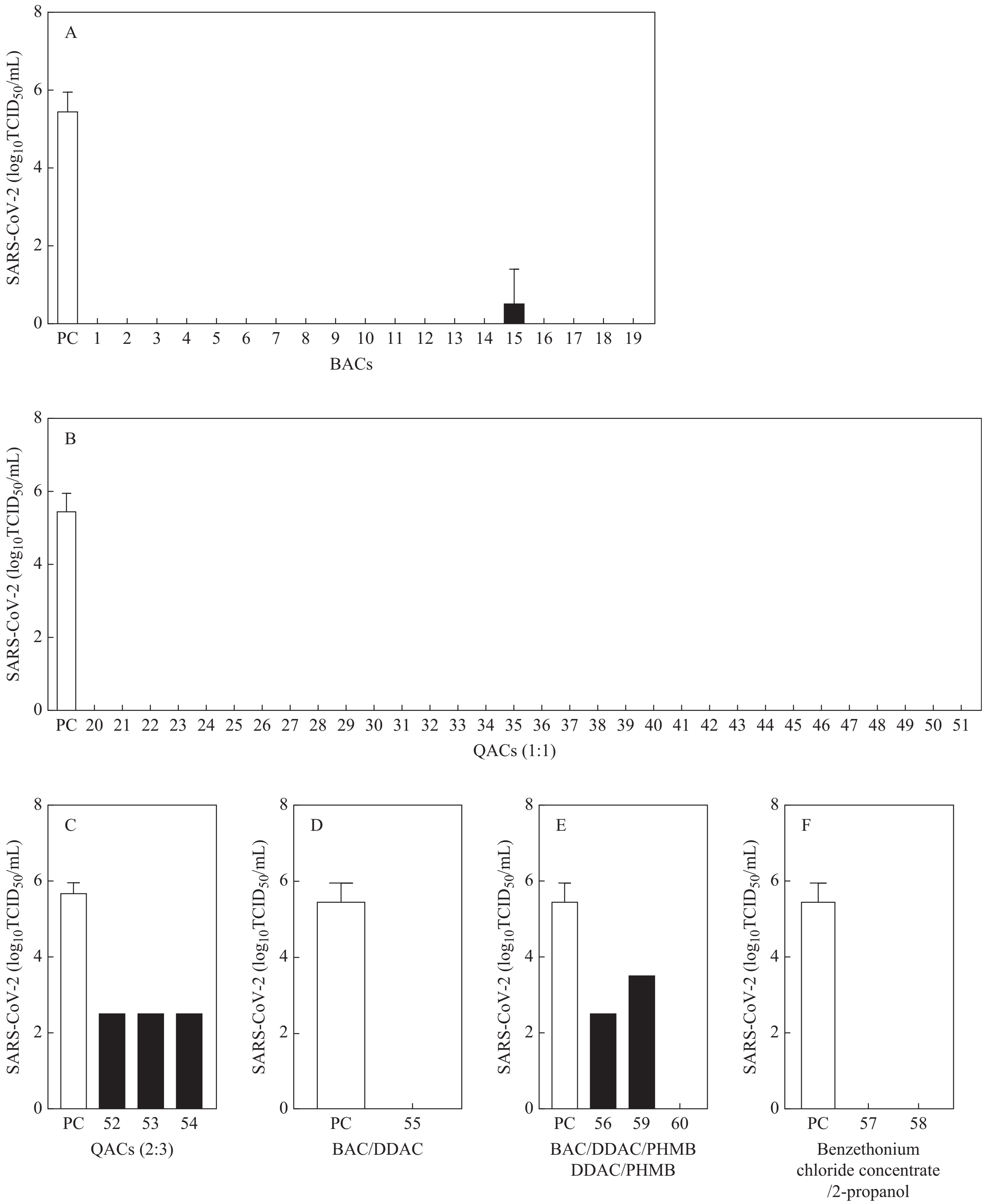
Evaluation of disinfectant cytotoxicity

The disinfectants were diluted with ultrapure deionized water, mixed in a 1:1 ratio with DMEM without serum, and incubated at recommended time points (Table S2, see online supplementary material). Following incubation, they were neutralized using DMEM containing 10% FBS, and the mixture was serially diluted with DMEM without serum (10^{-1} and 10^{-2}). Vero E6 cells (2 x 10^4 cells/well) were treated with diluents and incubated for 3 days, then harvested by trypsinization, stained with trypan blue, and the numbers of total and living cells were counted using a Luna-II auto cell counter (Logos Biosystems, Gyeonggi-do, South Korea). These experiments were performed in triplicate. In addition, the effect of disinfectants on cell viability was measured using the economical cell counting kit 8 (CCK-8) (Abbkine, Wuhan, China). Cell viability was indicated as mean ± SD of the triplicate samples.

Results

Commercial disinfectant efficiency against SARS-CoV-2

The virucidal effects of 72 commercially available surface disinfectants were analysed for their effect against SARS-CoV-2, and categorized as shown in Table I. The disinfectants were classified according to ingredients, and numbered from 1 to 72. Detailed information (disinfectant name, usage concentration, duration rate, exposure time, etc.) is provided in Table S1, see online supplementary material. The 19 disinfectants containing 0.05–0.4% BAC exhibited 90–100% virucidal efficacy against SARS-CoV-2 after 5–10 min of exposure. QACs comprised 80% N-alkyl dimethyl ethyl benzyl ammonium chloride, and alkyl dimethyl benzyl ammonium chloride exerted a differing effect against SARS-CoV-2 according to the ratio of the formulated ingredients. SARS-CoV-2 was inactivated completely by 0.02–0.07% QAC (1:1) disinfectants, whereas 0.04–4% QAC (2:3) disinfectants inactivated SARS-CoV-2 by approximately 50% within 10 min (Figure 1B,C). The disinfectants based on 0.4% BAC/didecyldimethylammonium chloride (DDAC) exhibited similar efficacy as the disinfectants based on BAC alone (Figure 1D). However, disinfectants based on BAC/DDAC/polyhexamethylene biguanide hydrochloride (PHMB) inactivated SARS-CoV-2 by approximately 50%. Moreover, the disinfectants based on 0.0205–0.14% DDAC/PHMB exhibited a variable SARS-CoV-2 inactivation rate of approximately 30–100% after 5–10 min of exposure (Figure 1E). These results confirmed that PHMB had no significant virucidal effect on SARS-CoV-2 in particular. The 0.28% benzethonium chloride concentrate/2-propanol-based disinfectants inactivated SARS-CoV-2 completely after 3–10 min of exposure (Figure 1F). Four alcohol-based disinfectants, such as 83% ethanol or 60% propanol mixed with ethanol, led to the complete inactivation of SARS-CoV-2 after 10 min of exposure (Figure 1G). Equal efficiency against SARS-CoV-2 was shown by two disinfectants comprising 0.00108–0.0011% sodium dichlorosiocyanyrate (Figure 1H), one disinfectant comprising 0.5% hydrogen peroxide (Figure 1I) and two disinfectants comprising 0.497% potassium peroxymonosulfate (Figure 1J) after 10–15 min of exposure. In contrast, two peracetic-acid-based disinfectants at 0.0173% showed 6.8–56.28% inactivation efficacy against SARS-CoV-2 after 10 min of exposure (Figure 1K). Furthermore, one citric-acid-based disinfectant at 0.4% could not inactivate SARS-CoV-2 (Figure 1L). These results suggest that most surface disinfectants inactivated SARS-CoV-2 effectively, but showed differences in inactivation efficacy depending on the ingredients or their combinations.


A
B
C
D
E
F
SARS-CoV-2 ($log_{10}TCID_{50}$/mL)
BACs
QACs (1:1)
QACs (2:3)
BAC/DDAC
BAC/DDAC/PHMB
DDAC/PHMB
Benzethonium
chloride concentrate
/2-propanol
PC

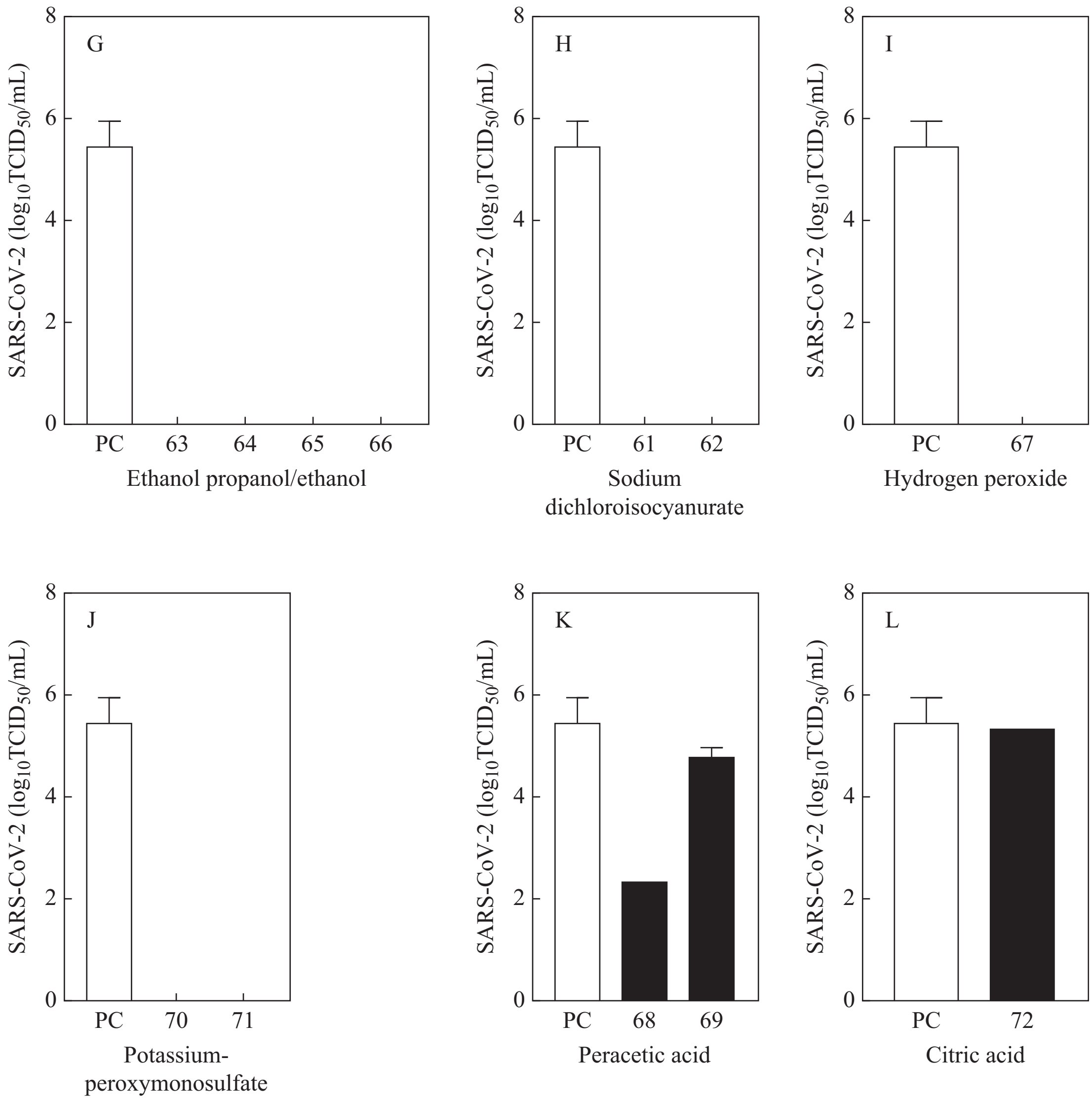


Figure 1. Inactivation of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) by 72 commercially available disinfectants. The SARS-CoV-2 solution was incubated with each disinfectant for the indicated time and concentration, and then inoculated in Vero E6 cells. The log value of virus titre was determined using the 50% tissue culture infectious dose assay. The disinfectants used included 32 benzalkonium chloride (BAC)-based products (A), 32 quaternary ammonium compound (QAC) (1:1)-based products (B), three QAC (2:3)-based products (C), one BAC/didecyldimethylammonium chloride (DDAC)-based product (D), one BAC/DDAC/polyhexamethylene biguanide hydrochloride (PHMB)-based product and two DDAC/PHMB-based products (E), two benzethonium chloride concentrate/2-propanol-based products (F), three ethanol-based products and one propanol/ethanol-based product (G), two sodium dichloroisocyanurate-based products (H), one hydrogen peroxide-based product (I), two potassium peroxymonosulfate-based products (J), two peracetic acid-based products (K) and one citric acid-based product (L). Graphs show the mean and standard deviation through three independent experiments.

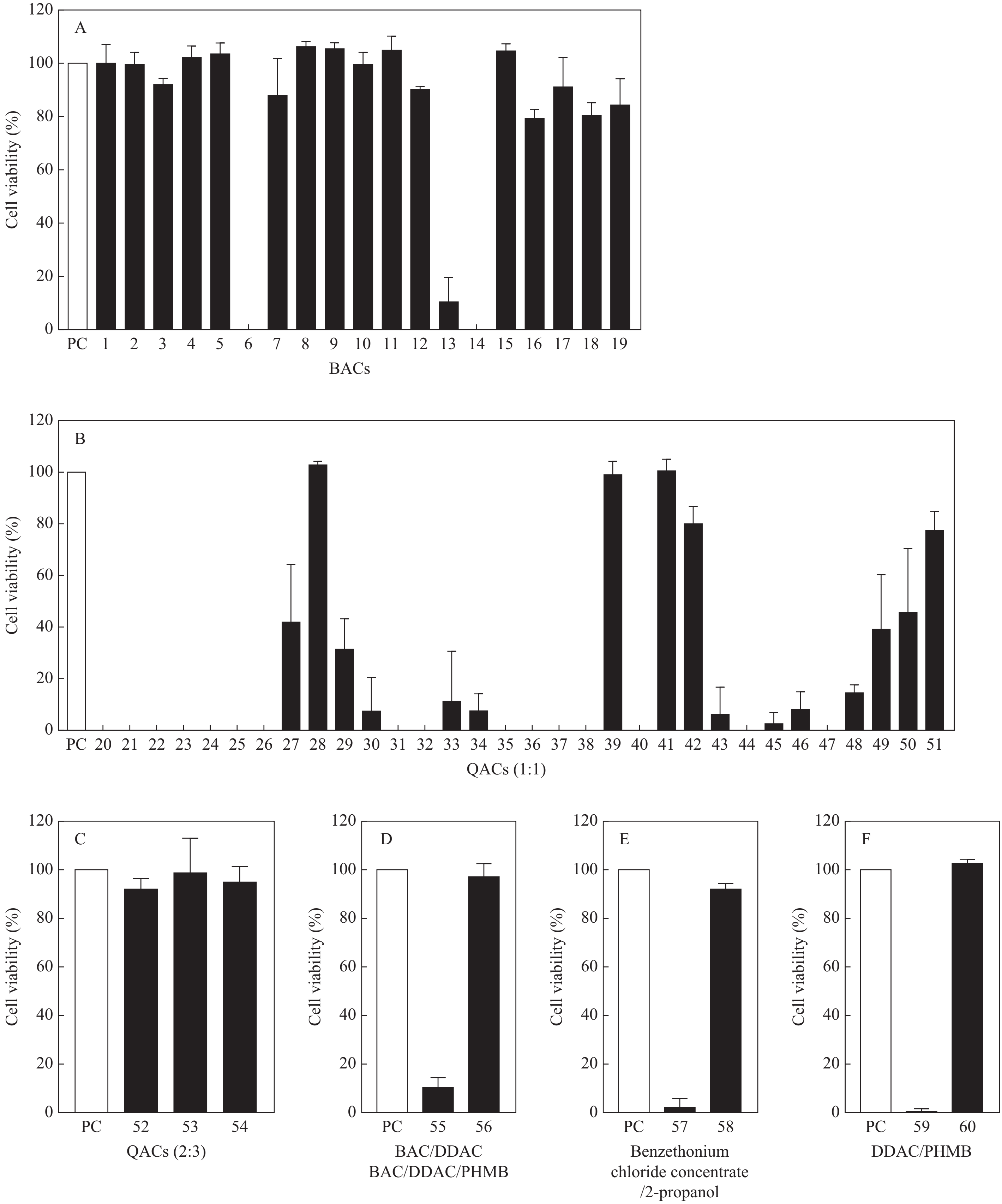
Cytotoxicity of commercial disinfectants

A cell viability assay was conducted to evaluate the cytotoxicity of 72 commercially available surface disinfectants in the same virucidal conditions (Table II). More detailed information on the cytotoxicity tests for each disinfectant is presented in Table S2 (see online supplementary material). Among the 19 BAC-based disinfectants, 12 exhibited low (<10%) cytotoxicity and four exhibited <20% cytotoxicity. Conversely, Disinfectants No. 6 and No. 14 exhibited high (100%) cytotoxicity, and Disinfectant No. 13 exhibited >80% cytotoxicity (Figure 2A). Among the 32 1:1 formulated QAC-based disinfectants, five exhibited <20% cytotoxicity and 27 exhibited >50% cytotoxicity (Figure 2B). Interestingly, the three 2:3 formulated QAC-based disinfectants exhibited no cytotoxicity (Figure 2C). The BAC/DDAC-based disinfectant was highly cytotoxic, whereas the BAC/DDAC/PHMB-based disinfectant was not cytotoxic (Figure 2D). Regarding the two benzethonium chloride concentrate/2-propanol-based disinfectants, Disinfectant No. 57 was highly cytotoxic but Disinfectant No. 58 was not cytotoxic (Figure 2E). Similarly, of the DDAC/PHMB-based disinfectants, Disinfectant No. 59 was highly cytotoxic but Disinfectant No. 60 was not cytotoxic (Figure 2F). The disinfectants based on sodium dichloroisocyanurate, ethanol or propanol mixed with ethanol, peracetic acid, potassium

Table II
Cytotoxicity of commercial surface disinfectants including various active ingredients against severe acute respiratory syndrome coronmavirus-2

Number of product	Ingredient	Concentration (%)	Exposure time (min)	Cell viability (%)			
				10^{-1}	10^{-2}	10^{-3}	10^{-4}
19	BAC	0.05–0.4	5–10	81.166 ± 3.804	107.051 ± 1.552		
32	Quaternary ammonium compound (1:1)	0.02–0.07	10	23.695 ± 7.391	106.445 ± 2.507		
3	Quaternary ammonium compound (2:3)	0.04–4	10	95.238 ± 5.207	106.613 ± 1.63		
1	BAC/DDAC	0.4	10	10.3 ± 4.192	0 ± 0	116.023 ± 3.887	109.537 ± 5.868
1	BAC/DDAC/PHMB	0.00625	10	97.159 ± 5.381	114.54 ± 4.056		
2	Benzethonium chloride concentrate/2-propanol	0.28	3–10	47.112 ± 1.026	104.11 ± 2.459		
2	DDAC/PHMB	0.0205–0.14	5–10	51.612 ± 0.518	103.883 ± 5.854		
2	Sodium dichloroisocyanurate	0.00108–0.0011	15	102.892 ± 0.185	109.073 ± 0.441		
3	Ethanol	83	10	114.215 ± 2.153	109.877 ± 2.37		
1	Propanol/ethanol	60	10	120.39 ± 3.319	115.218 ± 2.101		
1	Hydrogen peroxide	0.5	10	0 ± 0	120.093 ± 2.163		
2	Peracetic acid	0.0173	10	114.073 ± 1.534	116.7444 ± 0.412		
2	Potassium peroxymonosulfate	0.497	10	107.943 ± 0.761	115.1 ± 0.863		
1	Citric acid	0.4	10	102.892 ± 0.185	109.073 ± 0.441		

BAC, benzalkonium chloride; DDAC, didecyldimethylamonium chloride; PHMB, polyhexamethylene biguanide hydrochloride; quaternary ammonium compound, 80% N-alkyldimethylethylbenzylammonium chloride:alkyldimethylbenzylammonium chloride (1:1 or 2:3).


A
Cell viability (%)
0
20
40
60
80
100
120
PC 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
BACs
B
Cell viability (%)
PC 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51
QACs (1:1)
C
PC 52 53 54
QACs (2:3)
D
PC 55 56
BAC/DDAC
BAC/DDAC/PHMB
E
PC 57 58
Benzethonium
chloride concentrate
/2-propanol
F
PC 59 60
DDAC/PHMB

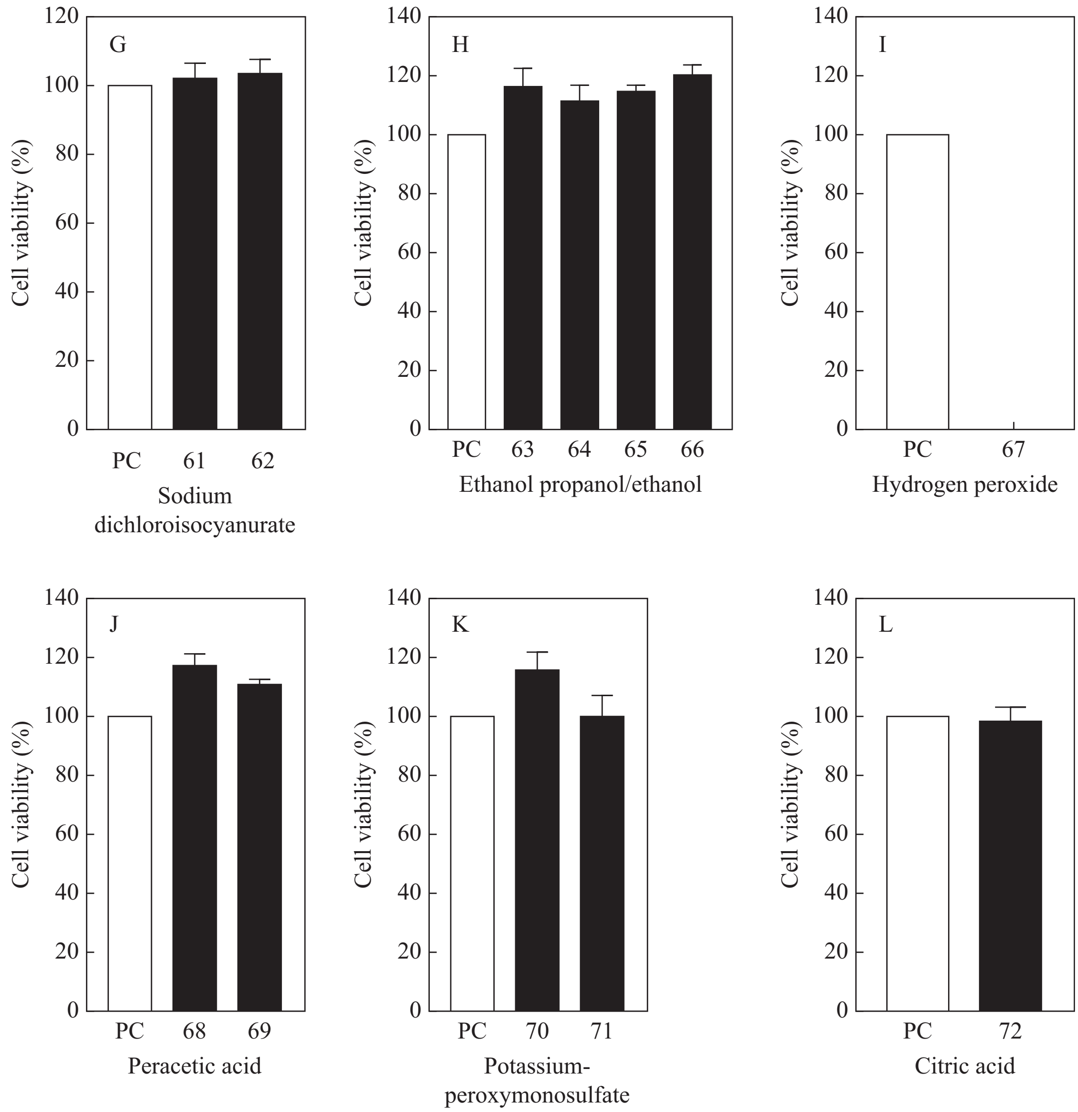


Figure 2. Evaluation of the cytotoxicity of 72 commercially available disinfectants. The disinfectants were added to Vero E6 cells for the indicated time and concentration. After 72 h, cell viability was determined by counting the living and proliferating cells. The disinfectants used included 32 benzalkonium chloride (BAC)-based products (A), 32 quaternary ammonium compound (QAC) (1:1)-based products (B), three QAC (2:3)-based products (C), two BAC/didecyldimethylammonium chloride (DDAC)-based and BAC/DDAC/polyhexamethylene biguanide hydrochloride (PHMB)-based products (D), two benzethonium chloride concentrate/2-propanol-based products (E), two DDAC/PHMB -based products (F), two sodium dichloroisocyanurate-based products (G), three ethanol-based products and one propanol/ethanol-based product (H), one hydrogen peroxide-based product (I), two peracetic acid-based products (J), two potassium peroxymonosulfate-based products (K) and one citric acid-based product (L). Cell viability is indicated as mean ± standard deviation of triplicate samples.

peroxymonosulfate and citric acid were not cytotoxic (Figure 2G,H,J,K,L). However, the hydrogen-peroxide-based disinfectant exhibited high cytotoxicity (Figure 2I).

Virucidal efficacy of disinfectants against SARS-CoV-2 between organic and inorganic conditions

In order to evaluate the virucidal efficacy of the disinfectants against SARS-CoV-2 in environmental conditions with low or high levels of organic matter, several concentrations of a disinfectant were tested in inorganic and organic conditions because the survival rate of the virus was higher in organic conditions than in inorganic conditions [32,33]. SARS-CoV-2 activity was decreased up to 4 $\log_{10}$ by 0.000071% QACs in inorganic conditions without cytotoxicity. However, 0.001% QAC was required for SARS-CoV-2 inactivation of up to 4 $\log_{10}$ in organic conditions, but this concentration was highly toxic (Table III and Table S3, see online supplementary material). In inorganic conditions, 0.016% sodium hypochlorite was required for the complete inactivation of SARS-CoV-2, but in organic conditions, 0.2% sodium hypochlorite was required (Table III and Table S4, see online supplementary material). Conversely, 50% ethanol and 2% citric acid exhibited similar virucidal efficacy in organic and inorganic conditions (Table III and Table S5, see online supplementary material). These results suggest that the virucidal efficacy of disinfectants can be

Table III
Effective concentration of various ingredients in two experimental conditions

Ingredient	Concentration (%)	Exposure time (min)	Reduction concentration up to 4 log 10 against SARS-CoV-2 (%)		Cell viability (%)	
			Inorganic (mineral)	Organic (5% FBS)	Inorganic (mineral)	Organic (5% FBS)
Quaternary ammonium compound (1:1)	1	30	0.000714	0.001	90 ± 8.9	20 ± 1.8
Sodium hypochloride	8		0.016	0.2	86.6 ± 3.1	95.2 ± 5.8
Ethanol	100		50	50	94 ± 6.1	90.2 ± 7.1
Citric acid	40		2	2.66	94.4 ± 4.8	95.5 ± 2.2

SARS-CoV-2, severe acute respiratory syndrome coronavirus-2; FBS, fetal bovine serum; quaternary ammonium compound, 80% N-alkyldimethylethylbenzylammonium chloride:alkyldimethylbenzylammonium chloride (1:1).

influenced by organic conditions depending on the ingredients in the disinfectant.

Discussion

The main route of infection for SARS-CoV-2 is transmission through respiratory droplets, but contact with contaminated surfaces, such as plastic, glass, paper and metal, may also be important. Several recent studies have reported that SARS-CoV-2 can survive for up to 3 days on various inanimate surfaces [13,15]. WHO and the Centers for Disease Control and Prevention recommend the use of safe and effective disinfectants when cleaning and disinfecting surfaces. Various ingredients, known as biocidal agents, have been applied widely in commercial disinfectants. Among them, ethanol is a traditional ingredient for cleaning surfaces or eliminating microbes. Disinfectants comprising 62—71% ethanol can reportedly inactive coronaviruses efficiently on surfaces after 1 min of exposure [19,34]. The present study showed that all alcohol-based disinfectants inactivated SARS-CoV-2 completely without causing cytotoxicity (Tables I and II). As alcohol-based disinfectants decompose to oxygen, water and acetic acid, these oxidizing agents are recognized as safe disinfectants. Unlike alcohol-based disinfectants, hydrogen peroxide triggers cytotoxicity in various cell types [35,36]. Previous studies reported that cell damage occurs following exposure to >100 μM hydrogen peroxide [37]. The present study showed complete SARS-CoV-2 inactivation by a high concentration of hydrogen peroxide ($\sim$150 mM) after 10 min of exposure; however, this exhibited cytotoxicity. (Tables I and II). In the cytotoxicity assessment, 1% of peracetic acid induced cell death, predominantly by necrosis [38]. In contrast, cell damage could not be observed in cells treated with 0.0173% peracetic acid during SARS-CoV-2 inactivation (6.8—56.28%) after 10 min of exposure (Table II). An oxidizing agent, potassium peroxymonosulfate, and the chemical compound sodium dichloroisocyanurate have been used to disinfect water in the food industry [39,40]. Both products comprising 0.497% potassium peroxymonosulfate or 0.00108—0.0011% sodium dichloroisocyanurate inactivated SARS-CoV-2 sufficiently without triggering any cell damage (Tables I and II). Citric acid is an approved disinfectant against foot-and-mouth disease virus in the Republic of Korea [28]. Citric acid reportedly exhibits low acute toxicity and no genotoxicity due to rapid degradation because of high environmental mobility [41]. Despite the lack of cytotoxicity, a commercial product comprising 0.4% citric acid did not show any significant effect, while 2.6—10% citric acid inactivated SARS-CoV-2 completely without cytotoxicity (Table S5, see online supplementary material). QACs, comprised as single compounds or mixtures, are widely used as biocidal and virucidal agents, applied in commercial products including personal hygiene, domestic and cosmetic products [42,43]. However, the toxicity of QACs to humans and the environment has been hotly debated [44,45]. In addition, various mixed products, including or excluding BAC, showed differences in cell viability and SARS-CoV-2 inactivation according to the mixture of ingredients (Table II). The differing effects of mixed products may be caused by the generation of toxic substances during the manufacturing process, or by high concentrations and exposure times.

All experiments determined the virucidal effect of various commercial disinfectants against SARS-CoV-2 under inorganic conditions. The efficacy of a disinfectant against viruses could change under organic experimental conditions [28,46]. In the present study, the effective concentrations of four representative chemical compounds were evaluated as disinfectant components in organic and inorganic conditions. QACs and sodium hypochlorite required a 10-fold higher concentration to reduce SARS-CoV-2 activity by up to 4 $\log_{10}$ in organic conditions compared with inorganic conditions. However, ethanol and citric acid exhibited similar virucidal activity at the same concentration in organic and inorganic conditions. Organic matter could interfere with virucidal activity, depending on the ingredients in the disinfectant. The virucidal activities of all disinfectants were assessed by an ASTM E1052-20, known as the suspension test method [47].

The surface test method supported incorrect results due to the low recovery rate of the reacting solution containing SARS-CoV-2 in preliminary tests (data not shown). In conclusion, the efficacy of various commercially formulated disinfectants against SARS-CoV-2, and their cytotoxic effects, were evaluated. The results indicate that currently available ingredients can be used to prevent SARS-CoV-2 infection. In addition, these results will be available as essential data in the disinfection guidelines for use by disinfectant ingredients.

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Conflict of interest statement

None declared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhin.2022.09.011.

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