The new coronavirus disease 2019 (COVID-19) is posing a dire health threat to the world. It has spread to more than 202 countries, and over 470,000 cases have been confirmed globally [1]. Approximately 9,241 cases have been confirmed in Korea as of March 26, 2020 [2], and the increasing numbers of patients are causing a significant medical burden. The virus is not a conventional coronavirus that infects the human body, but is an animal-originated virus adapted to the human body as a highly contagious pathogen [3].

The frontline protection primarily used in pandemic situations is vaccination. In addition, therapeutic agents for the disease should be available [4]. However, as of now, no vaccine has been developed for COVID-19, and it is expected that a vaccine will take a relatively long time to become available for public use. Recently, considerable efforts have been made to find an effective treatment for COVID-19 by repurposing or combining existing drugs [5].

Under this emergency situation, it is especially important for high-risk individuals to thoroughly prevent COVID-19 infection by maintaining personal hygiene and using protective equipment such as masks [6]. Personal protective equipment (PPE) plays a very important role in controlling the spread of diseases through direct or indirect contact exposure. Viruses that can cause respiratory symptoms such as coronavirus,
influenza virus, or rhinovirus are transmitted through contact with respiratory epithelial cells in the form of droplets or aerosols [7]. Recently, the increasing demand for PPE in this pandemic situation has resulted in a shortage of masks and protective clothing in several essential environments such as hospitals. Thus, it is necessary to develop effective ways to either use PPE for longer periods of time or improve their protective efficacy.

There have been many attempts to develop safer and more effective disinfectants, for example, a long-lasting physical disinfectant, using carbon-nanostructures [8] or salt crystals [9]. Surface-coating disinfectants are different from conventional disinfectants in terms of their mechanism of action and the duration of their effects. Organosilicon (3-(trimethoxysilyl) propyldimethyl octadecyl ammonium chloride, Si-QAC), which was used in this experiment, is a surface-coating disinfectant that forms spike-like structures on various surfaces and puts pressure on cell membranes using its protruding structure; therefore, it is expected to exert physical antimicrobial effects (Fig. 1). In this article, we examined the potential use of Si-QAC as an antimicrobial to disinfect PPE.

To conduct the disinfection efficacy test, we used three types of commercially available healthcare masks (HDmedis, Bucheon, Korea; Hyundai Chemical, Seoul, Korea; and Welkeeps, Seoul, Korea) and four types of protective clothing (Mtech STS, Daejeon, Korea; Yuhan-kimberly, Seoul, Korea; 3M, St. Paul, MN, USA; and DuPont, Wilmington, DE, USA).

In the control group, the materials were artificially contaminated with either influenza virus (A/NWS/33(H1N1), 10^7 tissue culture infectious dose [TCID]/mL; H9N2, 10^8 TCID/mL) or Salmonella typhimurium (10^8 CFUs/mL) as pathogens by spraying 100 µL of the sample of each pathogen on the test materials from a distance of 25 cm. In the experimental group, the test materials were coated with Si-QAC (SDpro; SDLab Korea, Seoul, Korea) by spraying 4 mL/m² of the disinfectant before contamination with the same amount of Salmonella or influenza samples. Antimicrobial or antiviral effects were measured by culturing the pathogens from the PPE in either nutrient agar or Madin-Darby Canine Kidney cell culture.

We also examined the efficacy of microbial contamination inhibition under field conditions by wearing disinfectant-
coated or non-coated protective clothing during the processes of transporting, packing, and cleaning in a food-processing factory. The used protective clothing were individually packaged and transported to the lab. After using the protective clothing for 8 hours, the number of bacteria was measured by swabbing the clothes in the middle of the neck, left sleeve, and hem of the clothing and dissolving the swabs in PBS for subsequent microbial culture.

The average reduction in influenza virus in the protective clothing was $10^{2.7}$ and $10^{4.1}$ TCID$_{50}$/mL for samples from which the virus was retrieved immediately and after 15 minutes, respectively, compared to the controls (Fig. 2A). For mask samples, after 30 minutes of reaction, the average reduction was $10^{2.5}$ TCID$_{50}$/mL in viral tests; a 115-fold reduction was observed in the bacterial tests (Fig. 3A, B). The antimicrobial effects lasted at least 7 days (Fig. 3C). In the field test, results varied slightly depending on the type of activity and the location of the measurement; however, on average,
the number of bacteria measured was about 30 times lower in the experimental group than in the controls (Fig. 2B).

In this study, we examined the effectiveness of applying surface-coating disinfectant onto PPE such as masks and protective clothing. It was observed that applying the disinfectant significantly decreased the bacterial and viral contamination on the surface. Tamimi et al. [10] and Orti-Lucas and Munoz-Miguel [11] also indicated that microbial contamination can be reduced via the surface coating of equipment with various substances, which is in agreement with our results.

There is an increasing demand for PPE to prevent COVID-19 infection, resulting in shortages of masks and other items. This often results in the need to use PPE for longer periods of time or even reuse them, which may reduce the demand for PPE. Based on the results of our study, it is expected that PPE coated with Si-QAC would provide a higher degree of antibacterial and antiviral protective effects. According to Tomas et al. [12], medical personnel can be contaminated while removing their soiled gloves and gowns. Thus, it is expected that the use of surface-coating disinfectants may reduce the risk of spreading pathogens upon disposal of used PPE.

The surface-coating disinfectant used in this test inactivates the pathogen by damaging the envelope of the pathogen and exerting its physical structure-based mechanism of action [13]. Damage to cell membranes leads to the antimicrobial effect. The longer the duration of interaction between the nanostructure and bacterial cell, the greater the extent of damage, which results in the bactericidal activity; our results are consistent with this theory. In contrast, a virus is relatively small in size; therefore, the disinfectant exerts less pressure on the surface of the virus compared to fungi and bacteria. Thus, the reduction in viral titer is considered to be the result of not only simple damage to the viral envelope but also the trapping phenomenon caused by the electrical force exerted by nanostructures. Recently, Quan et al. [9] reported a similar concept of disinfection using salt crystals. They coated a mask filter with salt to cause the virus to quickly lose its infectivity. The mechanism of action of the surface-coating disinfectant used in this experiment is quite different from that of the salt crystals because this agent adheres to the surface of the PPE via covalent bonding. Thus, the application of this disinfectant to surfaces with high probability of pathogen contamination, such as ambulances or medical facilities, is likely to have a significant disinfection effect. This would be helpful to people who are at a high risk of exposure to pathogens, such as patients and hospital/health workers.

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References

1. World Health Organization. Novel coronavirus (COVID-19) situation [Internet]. Geneva: World Health Organization; c2020 [cited 2020 Mar 17]. Available from: https://experience.arcgis.com/experience/685d0ace521648f8a5beeeee1b9125cd.
2. Ministry of Health and Welfare. Coronavirus disease 2019 (COVID-19) [Internet]. Sejong: Ministry of Health and Welfare; c2020 [cited 2020 Mar 17]. Available from: http://ncov.mohw.go.kr/index_main.jsp.
3. Li X, Zai J, Zhao Q, et al. Evolutionary history, potential intermediate animal host, and cross-species analyses of SARS-CoV-2. J Med Virol 2020;92:602-11.
4. Shang W, Yang Y, Rao Y, Rao X. The outbreak of SARS-CoV-2 pneumonia calls for viral vaccines. NPJ Vaccines 2020;5:18.
5. Zhou G, Chen S, Chen Z. Back to the spring of 2020: facts and hope of COVID-19 outbreak. Front Med 2020;14:113-6.
6. Mahase E. Covid-19: hoarding and misuse of protective gear is jeopardizing the response, WHO warns. BMJ 2020; 368:m869.
7. Nash AA, Dalziel RG, Fitzgerald JR. Mims’ pathogenesis of infectious disease. London: Academic Press; 2015.
8. Upadhyay RK, Soin N, Roy SS. Role of graphene/metal oxide composites as photocatalysts, adsorbents and disinfectants in water treatment: a review. RSC Adv 2014;4: 3823-51.
9. Quan FS, Rubino I, Lee SH, Koch B, Choi HJ. Universal and reusable virus deactivation system for respiratory protection. Sci Rep 2017;7:39956.
10. Tamimi AH, Carlino S, Gerba CP. Long-term efficacy of a
self-disinfecting coating in an intensive care unit. Am J Infect Control 2014;42:1178-81.

11. Orti-Lucas RM, Munoz-Miguel J. Effectiveness of surface coatings containing silver ions in bacterial decontamination in a recovery unit. Antimicrob Resist Infect Control 2017;6:61.

12. Tomas ME, Kundrapu S, Thota P, et al. Contamination of health care personnel during removal of personal protective equipment. JAMA Intern Med 2015;175:1904-10.

13. Ivanova EP, Hasan J, Webb HK, et al. Bactericidal activity of black silicon. Nat Commun 2013;4:2838.