Polarity-Dominated Stable N97 Respirators for Airborne Virus Capture Based on Nanofibrous Membranes

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Abstract: The longevity and reusability of N95-grade filtering facepiece respirators (N95 FFRs) are limited by consecutive donning and disinfection treatments. Herein, we developed stable N97 nanofibrous respirators based on chemically modified surface to enable remarkable filtration characteristics via polarity driven interaction. This was achieved by a thin-film coated polyacrylonitrile nanofibrous membrane (TFPNM), giving an overall long-lasting filtration performance with high quality factor at 0.42 Pa⁻¹ (filtration efficiency: over 97%; pressure drop: around 10 Pa), which is higher than that of the commercial N95 FFRs (0.10–0.41 Pa⁻¹) tested with a flow rate of 5 L min⁻¹ and the 0.26 μm NaCl aerosol. A coxsackie B4 virus filtration test demonstrated that TFPNM also had strong virus capture capacity of 97.67%. As compared with N95 FFRs, the TFPNM was more resistant to a wider variety of disinfection protocols, and the overall filtration characteristics remained N97 standard.

Introduction

Filtering facepiece respirators (FFRs) have become a global protection pathway with the air pollution growing as a worldwide concern. Polluted air contained particular matter (PM) not only leads to health threat to people, but also influences climate and ecosystems.[1] Aimed at PM₁₀ and PM₂₅ (particle size below 2.5 and 10 μm, respectively), membrane-based air filters have been explored to capture the PM from polluted air.[1a,2] However, for dangerous airborne particulates, including viral aerosols, the conventional air filters could not enable efficient filtration of these particulates.

In 2019, a respiratory disease broke out and developed into a rapid spread impact across the globe with more than 200 countries involved. This fatal disease is named as Coronavirus disease 2019 (COVID-19), which is a universal pandemic caused by the novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The size of COVID-19 virus is at 60–140 nm.[3] It has been authoritative demonstrated that the dominant transmittance route of COVID-19 is from infected individuals while coughing, sneezing and talking to uninfected people through the inbreathing of droplets or aerosols in the air.[4] For these dangerous airborne particulates, the N95 FFR is recommended to be used as personal protective equipment for healthcare aim, which is typically constructed by multiple layers of charged polypropylene (PP) fibers with diameters between 1–10 μm.[5] According to the announcement published by the United States Centers for Disease Control and Prevention’s (CDC’s) National Institute of Occupational Safety and Health (NIOSH) (document 42 CFR Part 84),[6] N95 is assigned to a filtration efficiency reached to or over 95% on 0.3 μm sized sodium chloride (NaCl) aerosols. The N95 FFRs have been professionally confirmed that their filtration efficiency should be adequate for daily protection.[7] Structurally, the micro-sized PP fibers are meltblown to build a lofty nonwoven with large void space and high layer thickness to provide sufficient physical barriers, but the high layer thickness would cause the increase of the corresponding pressure drop. To further improve the filtration efficiency and keep a relatively low resistance, the PP fibers are charged via corona discharge method to afford the N95 FFRs strong particulate adhesion via electrostatic charges (Figure 1a).[8] However, the charges could degrade during respiration, leading to a concomitant drop in filtration efficiency during use.[9] Furthermore, the N95 FFRs would be limited for reuse considering hygiene, damage, increased breathing resistance and the decreased filtration efficiencies.[9,10] To develop the healthy and safe reuse of the membrane-based respirators, the CDC has recommended effective disinfection treatments and sterilization methods, including chemical, thermal and radiative strategies. The proper disinfection techniques, such as heat treatments, are promising and nondestructive strategies to keep the filtration characteristics of N95 FFRs. However, solution-based disinfection methods could significantly degrade the filtration efficiency of N95 FFRs to unacceptable grade,[11] as these liquid-involved conditions would cause an inevitable corrosive effect to the surface electrostatic charges.[11]

Considering the problems that the existing charged respirator membranes could not overcome the aforementioned disadvantages, it is important to develop a facile approach to realize high filtration efficiency and stability.
Herein we introduce a polarity-dominated filtration approach based on nano- lined membrane materials (TFPM) for personal protective equipment (PPE) and are able to achieve effective personal filtration with a high safety factor.

**Results and Discussion**

The TF coated PAN nanofibrous membranes (TFPMs) were fabricated via electrospinning technique, and functionIALIZED through an interfacial polymerization process, resulting in light-yellow fabrics with alterable terminal groups (Figure 2a). The details of the polymerization process have been reported earlier. As shown in Figure 2b, the scanning electron microscopy (SEM) image displays an intertwined fibrous morphology, and the thin-film layer forms a uniform shell over the PAN nanofibers as revealed in the transmission electron microscopy (TEM) image. After the coating process, the TFPM remains an intertwined fibrous structure with the mean fiber diameter increasing from 400–500 nm to 500–600 nm (Supporting Information, Figure S1). Figure S2 shows the geometries of the TFPMs with different terminal groups, indicating no morphological changes on the fibers after modification. The alteration of the terminal groups results in a great difference in the surface tension of TFPMs, as well as the surface polarity. As previously reported by Fowkes,[14] the surface tension is composed of two independent parts: 1) a dispersive part ($\gamma_d$) and 2) a polar part ($\gamma_p$). The $\gamma_p$ values were precisely calculated via Owens-Wendt-Rabel-Kaelble (OWRK) method for each TFPM as compared with meltblown PP fabrics.[15] The $\gamma_p$ value of PP was calculated as $0.18 \pm 0.18$ mJ m$^{-2}$, indicating that PP meltblown fabrics is a nonpolar material. Compared with PP, the TFPMs possessed much stronger surface polarity, which could be altered through different coating from 2.99 mJ m$^{-2}$ (4-trifluoromethoxy-Ph-TF) to 66.09 mJ m$^{-2}$ (4-carboxyl-Ph-TF) as shown in Supporting Information, Table S1. The TF layer also showed a strong resistance in the organic solvents (Figure 2c and Supporting Information, Figure S3), which allowed the exposure of TFPM in harsh solvent environments. To further estimate the stability of the TFPMs, the membranes were exposed in various conditions, including high temperature (over 80°C), steam atmosphere (over 100°C with high humidity), 75% alcohol, chloride-based disinfecting water and Ultraviolet (UV) light. There was no

![Figure 2](image-url)
apparent damage and weight loss on the TFPNMs (Figure 2d), indicating no changes occurred on the fibrous geometry. The surface polarity of the TFPNMs upon these harsh treatments was evaluated. Compared with the initial TFPNM, the surface polarity of post-treated TFPNMs remained unchanged as shown in Supporting Information, Table S2. The stable surface polarity can enable stable polar-polar interaction between the membrane and PMs/aerosol, promising the TFPNMs great potential of reusability in various harsh conditions.

We firstly examined the capture capability of TFPNMs for various sizes of particulate matters (PMs) in order to simulate the air filtration in hazardous air-quality conditions. The burning incense was used in the laboratory to present hazardous PM level, which contains varieties of contaminants (PM, CO, CO2, NOX, and etc.). Figure 3a reveals the relationship between the pressure drop of TFPNMs and their basis weight and air flow. As can be seen, the increasing of the membrane thickness and the wind resistance could result in an apparent growth of pressure drop over the membranes. To keep a low resistance under high air flow (> 5 L min⁻¹), the optimal basis weight of all the TFPNMs was controlled at 10 g m⁻². Notice that, in Figure 3b, five TFPNMs with different surface polarity exhibit a large difference in the filtration efficiency. The relative results vary from 50.00% to 97.45% at PM₂.₅, according to the surface polarity from the lowest to the highest. It further confirms that the polar-polar interaction plays a dominant role in the PMs capture capability. Notably, the TFPNMs with cyano group and carboxyl group exhibit remarkably high filtration efficiency even over 97% (Figure 3b). To study the long effectiveness of the TFPNMs, the 4-cyan-ph-terminated TFPNM (CTFPNM), which possesses the same terminal group (-CN) as PAN molecule does, was tested in a continuous 10 h filtration process under a hazardous air-quality condition (with PM₁₀,₅ concentration >1000 μg m⁻³, PM₂.₅ number density >17 650 per m³). The results show great distinction between PAN nanofibrous membrane (PNM) and CTFPNM in the corresponding filtration efficiencies (Figure 3c). As for PNM, the filtration efficiency for PM₁₀ degraded from 97.10% to 94.57% and the filtration efficiency degraded from 99.67% to 99.42% for PM₂.₅ after 10 h. However, the filtration characteristic of CTFPNM remained stable, with filtration efficiencies over 97.00% and 99.90% for PM₁₀ and PM₂.₅, respectively, in 10 h.

Furthermore, CTFPNM and 4-carboxyl-ph-terminated TFPNM (cTFPNM) show outstanding filtration characteristics, especially the longevity, in a 24 h continuous blocking test with PM₁₀,₂₅ filtration efficiencies reaching to 99.90% (Supporting Information, Figure S4). A direct demonstration of the blocking of PMs over a TFPNM is shown in Figure 3d. The TFPNM (3.5 cm x 3.5 cm) was tightly fixed in the middle of two flanges, with the PM₂.₅ concentration over 1000 μg m⁻³ in the left bottle. As shown in Figure 3d, the right bottle could remain clear with the PM₂.₅ concentration in a superior level (< 1 μg m⁻³) after 1 h.

To study the filtration characteristics of TFPNMs compared with N95 FFRs, two TFPNMs with high surface polarity, CTFPNM and cTFPNM, were introduced for cubic NaCl aerosols filtration. All the TFPNM samples with the same basis weight at 10 g m⁻² were characterized with a flow rate of 5 L min⁻¹ and the NaCl (0.26 μm medium diameter) aerosol. As shown in Figure 4a and Supporting Information, Figure S5a, the filtration efficiencies of both CTFPNM and cTFPNM achieve at N97 grade and remain steady within a continuous 24 h filtration process. The basis weights of both TFPNMs increase to 13 g m⁻² due to the loading of NaCl aerosols within 24 h, which results in a slight increase of the corresponding pressure drops from 9–10 Pa to around 13 Pa (Figure 4b and Supporting Information, Figure S5b). The relatively low pressure drop demonstrates an appropriate respiratory resistance, giving the practicability of TFPNM applied as a filtering facepiece respirator. By contrast, N95 FFRs dominated by charged PP meltblown fabrics show obvious instability during filtering. As shown in Figure 4c, d, for the filtering layers of MEO-brand and 3Q-brand N95 FFRs, around 80% electrostatic charges broke away within 10 h. The remaining charges at 10–15% (0.20–0.30 kV) can still capture aerosols in the following 14 h, but the filtration efficiencies for N95 FFRs dropped below 95%. Meanwhile, when loading with more NaCl aerosols for 24 h, the N95 FFRs have an obvious increase of the pressure drops from 8 Pa to 15 Pa for MEO-brand and from 15 Pa to 25 Pa for 3Q-brand. The electrostatic effect was further studied on the filtration efficiencies of the TFPNMs. Their filtration efficiencies exhibit a slight increase to N98 grade for both charged cTFPNM and CTFPNM (Supporting Information, Figure S5c, d). However, the filtration efficiencies of these charged respirator membranes finally drop to N97 grade after
represents the filtration efficiency, $h_{\text{tp}}$ to 0.26 Pa and the mean diameter of influenza viruses is around 30 nm, into the filtration system. Where $\eta$ represents the filtration efficiency, $\Delta p$ is the pressure drop value under certain flow rate. The QF is universally used according to the WHO and recommended to be ranged over 0.05 Pa$^{-1}$. The overall filtration characteristics of the aforementioned respirators were investigated as shown in Figure 4, and the corresponding QFs were calculated and summarized in Supporting Information, Table S3. The initial QFs for both cTFPNM and CTFPNM are 0.34 Pa$^{-1}$, owing to the N97 grade filtration efficiency and relatively low pressure drop. After 10 h, the advantage of polarity-dominated TFPNMs on overall filtration performances becomes much more obvious with QFs at 0.34 Pa$^{-1}$ compared to the N95 FFRs with a lack of electrostatic charges (possessing poor QFs at 0.08 Pa$^{-1}$ to 0.26 Pa$^{-1}$). After 24 h, the pressure drops of TFPNMs can be maintained at around 13 Pa, and the filtration efficiencies keep comparable at N97 grade, therefore, the QFs of TFPNMs can reach to 0.28 Pa$^{-1}$. While the QFs for N95 FFRs appreciably drop to 0.06 Pa$^{-1}$ to 0.19 Pa$^{-1}$, owing to the unstable filtration efficiencies and relatively high pressure drops.

The cTFPNM (basis weight of 10 g m$^{-2}$) was deployed in viral aerosols to evaluate its filtration efficiency. The isolated small viruses could be more difficult to capture due to their teeny sizes. For example, the sizes of the picornaviruses are around 30 nm and the mean diameter of influenza viruses is around 120 nm. All these particulates with diameter under 0.3 μm are neglected in conventional filtration efficiency tests. In this work, we employed an infectious virus, Coxackie B4 virus (CV-B4), a tiny RNA virus (27–30 nm), into the filtration system. The viral solution was aerosolized at 0.26 μm medium diameter with a flow rate of 5 L min$^{-1}$ throughout the filtration test. We also performed viral filtration test over MEO-brand N95 FFR, to investigate its virus capture capability. As shown in Figure 5a, the cTFPNM
As shown in Figure 5b, most HeLa cells (right image) exhibited a relatively polyhedral cell shape (left image), as compared with the healthy HeLa cells (middle image). However, the CV-B4 virus in the compressed aerosols over MEO-brand N95 FFR can apparently cause the CPE of most HeLa cells (right image), leading to cell shrinkage, rounding and a cell release from the monolayer.

To investigate the virus penetrability across the respirator membranes, we studied the cytopathic effect (CPE) of CV-B4 in the HeLa cells. As shown in Figure 5b, most HeLa cells propagated in the filtered CV-B4 viral aerosols over cTFPNM remain a relatively polyhedral cell shape (left image), as compared with the healthy HeLa cells (middle image). However, the CV-B4 virus in the compressed aerosols over MEO-brand N95 FFR can apparently cause the CPE of most HeLa cells (right image), leading to cell shrinkage, rounding and a cell release from the monolayer. This is because that most viruses could be successfully captured over TFPNMs, yet the N95 FFR has insufficient capture capability of tiny viral aerosols (Supporting Information, Figure S6). Further virus titration test gave a degradation on the virus concentration from $10^5$ to $10^3$ TCID$_{50}$/0.1 mL over cTFPNM, also demonstrating its remarkable virus capture capability.

To investigate the reusability of TFPNMs, five commonly home-exercisable methods were operated on cTFPNM$_{95}$. (1) heat treatment with temperature at 80°C (High temperature above 70°C could lead to protein denaturation of SARS-CoV-2 over 5 min); (2) steam (100°C heat-based protein denaturation); (3) 75% alcohol (protein denaturation); (4) domestic chlorine-based solution (cellular denaturation, with chemical damage); (5) ultraviolet germicidal irradiation (DNA/RNA disruption, UVC 254 nm).

As seen in Supporting Information, Table S4, all the filtration efficiencies remain unchanged at N97 level after 9–10 Pa after 10 cycles (Figure 6a,b). However, the MEO-brand N95 FFR exhibited poor recyclability in 10 cycles upon some disinfection treatments (Figure 6c,d). The corresponding results after 10 cycles are illustrated in Figure 6. Significantly, the cTFPNMs deposited upon various disinfection treatments with a complete degradation on electrostatic charge quantity to 0 kV, which is far beyond N95 grade. Taking the MEO-brand N95 FFR as an example, large pores randomly exist in the meltblown samples (Supporting Information, Figure S8), leading to an unacceptable filtration efficiency at 68.58% and 57.33% in 75% alcohol and chlorine-based solution, respectively. The corresponding pressure drops change from 8 Pa to 10 Pa (in 75% alcohol) and 5 Pa (in chlorine-based solution), respectively (Supporting Information, Table S6). As for Dräger-brand N95 FFR, the apparent degradation can be observed upon UVGI treatment, with the filtration efficiency decay to 93.82%.

We further investigated the stability of different respirators upon various disinfections in multiple treatment cycles, and the corresponding results after 10 cycles are illustrated in Figure 6. Significantly, the cTFPNM deposited upon various disinfection treatments can maintain the corresponding filtration efficiencies at N97 level with pressure drops at 9–10 Pa after 10 cycles (Figure 6a, b). However, the MEO-brand N95 FFR exhibited poor recyclability in 10 cycles upon some disinfection treatments (Figure 6c, d). The filtration efficiencies were able to be retained over 95% after 10 cycles of heat and UVGI treatments. Treatments involving liquids and vapors, such as steam, alcohol, and household bleach, all led to degradation of the filtration efficiency, very likely due to the decay of the electrostatic charges, in addition to possible mechanical damage of the respirator membranes. Even worse, after 10 cycles, the MEO-brand N95 FFRs treated in both solution-based disinfection methods showed substantial degradation on filtration efficiencies to 65.52% (in 75% alcohol) and 51.18% (in chlorine-based solution).
**Conclusion**

We have developed a facile air filtration approach dominated by polarity interaction between the respirator membranes and the airborne PMs and aerosols. The electrospun PAN nanofibrous membranes with modified surface polarities (TFPNMs) give the air filtration N97 grade efficiency and show long effectiveness, excellent reusability and practicability as respirator membranes, which significantly overcome the disadvantages of the N95 FFRs caused by the unstable electrostatic charges. Compared with the charged nonpolar polypropylene (PP) microfibers, which capture the fine particulates mainly through electrostatic adsorption, the highly polar nanofibers in TFPNM have great capture capability of PMs and aerosols owing to the strong surface polarity. And the thin nanofibrous construction can provide strong physical barrier under low pressure drop, leading to remarkable practicability as FFRs. Furthermore, for PMs and aerosols under 0.3 μm, especially the dangerous viruses, the TFPNM enables more stable and highly efficient viral filtration compared with the N95 FFRs. Owing to the stably maintained surface polarity of TFPNMs, the filtration efficiency can keep at N97 grade upon multiple disinfection treatment cycles, including both physical and chemical methods. Therefore, the TFPNMs show great potential in achieving a healthy and safe reuse of the respirators for the public, having N97 grade filtration efficiency with prominent longevity, reuse potential and practicability. These advantages promise the polarity-dominated air filtration approach as a guidance in helping the public to raise the safety standard of using mask protection.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords:** materials science · N97 grade · reusability · thin films · virus capture

[1] a) C. Liu, P. C. Hsu, H. W. Lee, M. Ye, G. Zheng, N. Liu, W. Li, Y. Cui, *Nat. Commun.* **2015**, *6*, 6205; b) W. Cai, G. Wang, A. Santosso, M. J. McPhaden, L. Wu, F.-F. Jin, A. Timmermann, M. Collins, G. Vecchi, M. Lengaigne, M. H. England, D. Dommenget, K. Takahashi, E. Guilyardi, *Nat. Clim. Change* **2015**, *5*, 132–137; c) J. Lelieveld, J. S. Evans, M. F halis, D. Giannadaki, A. Pozzer, *Nature* **2015**, *525*, 367–371; d) D. Fang, B. Chen, K. Huabeck, R. Ni, L. Chen, K. Feng, J. Lin, *Sci. Adv.* **2019**, *5*, eaav4707.

[2] a) B. Wang, Q. Wang, Y. Wang, J. Di, S. Miao, J. Yu, *ACS Appl. Mater. Interfaces* **2019**, *11*, 43409–43415; b) K. Liu, C. Liu, P. C. Hsu, J. Xu, B. Kong, T. Wu, R. Zhang, G. Zhou, W. Huang, J. Sun, Y. Cui, *ACS Cent. Sci.* **2018**, *4*, 894–898.

[3] a) N. Zhu, D. Zhang, W. Wang, X. Li, B. Yang, J. Song, X. Zhao, B. Huang, W. Shi, R. Lu, P. Niu, F. Zhan, X. Ma, D. Wang, W. Xu, G. Wu, G. F. Gao, W. Tan, *N. Engl. J. Med.* **2020**, *382*, 727–733; b) Y. Zhu, D. Yu, Y. Han, H. Yan, H. Chong, L. Ren, J. Wang, T. Li, Y. He, *Sci. Adv.* **2020**, *6*, eab9999; c) K. K. Chan, T. C. Tan, K. K. Narayanan, E. Procko, *Sci. Adv.* **2021**, *7*, eaaf1738.

[4] J. Leap, V. Viligran, T. Cheema, *Crit. Care. Nurs. Q.* **2020**, *43*, 338–342.

[5] L. Liao, W. Xiao, M. Zhao, X. Yu, H. Wang, Q. Wang, S. Chu, Y. Cui, *ACS Nano* **2020**, *14*, 6348–6356.

[6] L. Rosenstock, *Infect. Control. Hosp. Epidemiol.* **1995**, *16*, 529–531.

[7] W. C. Hill, M. S. Hull, R. I. MacCuspie, *Nano Lett.* **2020**, *20*, 7642–7647.

[8] a) R. Dennis, B. C. Pourdeyhimi, A. S. Emanuel, D. Hubbard, *J. Sci. Med. Sport* **2020**, *2*, 1; b) S.-H. Huang, C.-W. Chen, Y.-M. Kuo, C.-Y. Lai, R. McKay, C.-C. Chen, *Aerosol Air Qual. Res.* **2013**, *13*, 162–171.

[9] E. Hossain, S. Bhadra, H. Jain, S. Das, A. Bhattacharya, S. Ghosh, D. Levine, *Phys. Fluids* **2020**, *32*, 093304.

[10] a) CDC, “Coronavirus Disease 2019 (COVID-19). In: Centers for Disease Control and Prevention”, can be found under https://www.cdc.gov/coronavirus/2019-ncov/ respirator-use-faq. html, **2020**; b) C. D. Vuma, J. Manganyi, K. Wilson, D. Rees, *Ann. Work Expo. Health* **2019**, *63*, 930–936.

[11] B. Cantaloube, G. Dreyfus, J. Lewiner, *J. Polym. Sci. Polym. Phys.* **1979**, *17*, 95–101.

[12] J. Xu, C. Liu, P. C. Hsu, K. Liu, R. Zhang, Y. Liu, Y. Cui, *Nano Lett.* **2016**, *16*, 1270–1275.

[13] a) S. Kuwabara, *J. Phys. Soc. Jpn.* **1959**, *14*, 527–532; b) S. A. Hossinei, H. V. Tafreshi, *Powder Technol.* **2010**, *201*, 153–160; c) K. W. Lee, B. Y. H. Liu, *Aerosol Sci. Technol.* **1981**, *1*, 35–46; d) J. Xue, T. Wu, Y. Dai, Y. Xia, *Chem. Rev.* **2011**, *119*, 5298–5415; e) Q. Wang, Y. Wang, B. Wang, Z. Liang, J. Di, J. Yu, *Chim. Sci.* **2019**, *10*, 6382–6389; f) J. Di, L. Li, Q. Wang, J. Yu, *ACS Chem. 2020*, *2*, 2280–2297; g) L. Pérez-Mañrique, J. Aburabi’e, P. Neelakanda, K.-V. Peinemann, *React. Funct. Polym.* **2015**, *86*, 243–247.

[14] a) F. M. Fowkes, *J. Phys. Chem.* **1962**, *66*, 382–382; b) F. M. Fowkes, *Ind. Eng. Chem.* **1964**, *56*, 40–52.

[15] a) D. K. Owens, R. C. Wendt, *J. Appl. Polym. Sci.* **1969**, *13*, 1741–1747; b) D. H. Kaebble, *J. Adhes.* **1970**, *2*, 66–81.

[16] a) B. Khalid, X. Bai, H. Wei, Y. Huang, H. Wu, Y. Cui, *Nano Lett.* **2017**, *17*, 1140–1148; b) T. C. Lin, G. Krishnaswamy, D. S. Chi, *Clin. Mol. Allergy* **2008**, *6*, 3.

[17] C. D. Zhangmeister, J. G. Radney, E. P. Vicenzetti, J. L. Weaver, *ACS Nano* **2020**, *14*, 9188–9200.

[18] Health Emergencies Preparedness and Response Team, *WHO*, **2020**.

[19] M. G. Rossmann, E. Arnold, J. W. Erickson, E. A. Frankenberger, J. P. Griffith, H. J. Hecht, J. E. Johnson, G. Kamer, M. Luo, A. G. Mosser, R. R. Rueckert, B. Sherry, G. Vriend, *Nature* **1985**, *317*, 145–153.

[20] A. Harris, G. Cardone, D. C. Winkler, J. B. Heymann, M. Brecher, J. M. White, A. C. Steven, *Proc. Natl. Acad. Sci. USA* **2006**, *103*, 19123–19127.

[21] a) L. Agueh-Oueoslai, H. Jaidane, S. Nane, S. Jrad-Battikh, S. B. Hamedi, D. Hobert, J. Gharbi, *Curr. Microbiol.* **2018**, *75*, 32–39; b) H. Jmii, A. Halouni, M. Maatouk, L. Chekir-Ghedira, M. Aouni, S. Fisson, H. Jaidane, *Microb. Pathog.* **2020**, *145*, 104235.

[22] a) E. A. Govorkova, G. Murti, B. Meignier, C. de Taisne, R. G. Webster, *J. Virol.* **1996**, *70*, 5519–5524; b) M. A. Salako, M. J. Carter, G. E. Kass, *J. Biol. Chem.* **2006**, *281*, 16296–16304.

[23] C. M. Carthy, D. J. Granville, K. A. Watson, D. R. Anderson, J. E. Wilson, D. Yang, D. W. C. Hunt, B. M. McManus, *J. Virol.* **1998**, *72*, 7669–7675.
[24] a) A. W. H. Chin, J. T. S. Chu, M. R. A. Perera, K. P. Y. Hui, H.-L. Yen, M. C. W. Chan, M. Peiris, L. M. M. Poon, *Lancet Microbe* 2020, 1, e10; b) M. E. Darnell, K. Subbarao, S. M. Feinstone, D. R. Taylor, *J. Virol. Methods* 2004, 121, 85–91; c) H. F. Rabenau, J. Cinatl, B. Morgenstern, G. Bauer, W. Preiser, H. W. Doerr, *Med. Microbiol. Immunol.* 2005, 194, 1–6; d) D. J. Viscusi, M. S. Bergman, B. C. Eimer, R. E. Shaffer, *Ann. Occup. Hyg.* 2009, 53, 815–827.

[25] P. N. Lelie, H. W. Reesink, C. J. Lucas, *J. Med. Virol.* 1987, 23, 297–301.

[26] a) G. Kampf, D. Todt, S. Pfaender, E. Steinmann, *J. Hosp. Infect* 2020, 104, 246–251; b) R. Thaper, B. Fagen, J. Oh, *Photochem. Photobiol. Sci.* 2021, 20, 955–965.

[27] a) W. B. Salter, K. Kinney, W. H. Wallace, A. E. Lumley, B. K. Heimbuch, J. D. Wander, *J. Occup. Environ. Hyg.* 2010, 7, 437–445; b) C. Dellanno, Q. Vega, D. Boessenberg, *Am. J. Infect. Control* 2009, 37, 649–652.

[28] D. Perdiz, P. Gróf, M. Mezzina, O. Nikaido, E. Moustacchi, E. Sage, *J. Biol. Chem.* 2000, 275, 26732–26742.