We are IntechOpen, the world’s leading publisher of Open Access books
Built by scientists, for scientists

5,600 Open access books available
138,000 International authors and editors
175M Downloads

154 Countries delivered to
TOP 1% Our authors are among the most cited scientists
12.2% Contributors from top 500 universities

WEB OF SCIENCE™
Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com
Chapter

Antiviral Coatings as Continuously Active Disinfectants

Luisa A. Ikner and Charles P. Gerba

Abstract

Antimicrobial surfaces and coatings have been available for many decades and have largely been designed to kill or prevent the growth of bacteria and fungi. Antiviral coatings have become of particular interest more recently during the COVID-19 pandemic as they are designed to act as continuously active disinfectants. The most studied antiviral coatings have been metal-based or are comprised of silane quaternary ammonium formulations. Copper and silver interact directly with proteins and nucleic acids, and influence the production of reactive free radicals. Titanium dioxide acts as a photocatalyst in the presence of water and oxygen to produce free radicals in the presence of UV light or visible light when alloyed with copper or silver. Silane quaternary ammonium formulations can be applied to surfaces using sprays or wipes, and are particularly effective against enveloped viruses. Continuously active disinfectants offer an extra barrier against fomite-mediated transmission of respiratory and enteric viruses to reduce exposure between routine disinfection and cleaning events. To take advantage of this technology, testing methods need to be standardized and the benefits quantified in terms of reduction of virus transmission.

Keywords: disinfection, virus, coating, continuously active, fomites

1. Introduction

Enteric and respiratory viruses can potentially be transmitted via contaminated environmental surfaces [1, 2]. Infectious viruses present on fomites may be transferred to the fingers and/or hands when touching various surface types under a broad spectrum of environmental conditions [3]. Transfer efficiency is affected by factors including virus species, inoculum size, and skin condition [4]. Subsequent contact with the eyes, nose, or mouth with contaminated fingers and hands may then provide access to susceptible human hosts [5]. Disinfection of environmental surfaces lowers the numbers of infectious microorganisms, thereby reducing the risk for transmission [6, 7]. However, such surfaces are subjected to continuous recontamination events, particularly in high-traffic areas and facilities including hospitals, daycare centers, schools and office buildings where fomites are more likely to serve as reservoirs of pathogens [8–10].

There are hundreds of liquid-based formulations that are registered as disinfectants with governmental regulatory agencies around the world, and a subset of those also carry label kill claims against non-enveloped and enveloped viruses. The efficacy testing that is required for the issuance of product label claims is performed using internationally-recognized standard test methods such as those produced by
the American Standard for Test Materials (ASTM) and the European Standard (EN), among others. Liquid disinfectants can be applied to hard, non-porous surfaces using spray devices, towelettes (wipes), or as bulk liquid volumes to address large, soiled areas. To achieve the antiviral inactivation claims specified on product labels, disinfectants must be used according to the manufacturer’s instructions which may require maintaining a completely wetted surface for up to 10 minutes. However, the habits and practices of product users are contrary to the directions specified on the label. A recent survey of American adults conducted on behalf of the American Cleaning Institute in 2020 revealed that 26% of respondents adhere to label directions during household disinfection routines; however, an equal percentage of those surveyed did profess to wiping surfaces until dry immediately after spraying with no adherence to contact time instructions [11]. An additional 16% of respondents claimed to use a single-pass method for disinfectant wipes rather than the multiple passes that are generally required to maintain surface wetness for several minutes.

The importance of correct disinfection usage has been of increased concern during the COVID-19 pandemic. Alternative disinfecting surface treatments that are capable of inactivating infectious agents, in particular viruses, are under research and development [12, 13]. A number of new and diverse antiviral coatings and films have been synthesized, and fixed or immobilized applications including solids (e.g., antimicrobial plastics), paints, and metals are increasingly of interest for their antiviral capabilities. The factors affecting virus survival and the efficacy of antiviral coatings are summarized in Table 1 and Figure 1.

| Factor          | Impact                                                                 |
|-----------------|------------------------------------------------------------------------|
| Type of virus   | Non-enveloped viruses are generally more resistant than enveloped viruses |
| Relative humidity | Drying rates of deposited viruses are affected, impacting viability    |
| Temperature     | Protein denaturation results in loss of structural integrity of virus   |
| Soil (dirt) load | Increased demand on antiviral actives, decreasing availability for virus inactivation |
| Coating composition | Mechanisms of antiviral action differ among viruses and vary according to formulation |
| Contact Time    | Time required for at least a 99.9% (3 log10) reduction in titer may range from minutes to hours |

Table 1. Factors that affect virus survival and efficacy of antiviral coatings [2, 14].

Figure 1. Continuously active antiviral surface coatings: a) coating applied to hard, non-porous surface demonstrates antiviral activity following virus deposition; b) coated surfaces are cleaned/disinfected with wiping action with passage of time, c) residual coating demonstrates continuous antiviral efficacy following surface cleaning events (Created in BioRender.com).
Antiviral Coatings as Continuously Active Disinfectants
DOI: http://dx.doi.org/10.5772/intechopen.101752

cOATINGS have been reviewed [2, 14] and include virus structure (i.e. enveloped, non-enveloped), the presence of organic soil (dirt), temperature, relative humidity, coating composition, and contact time (Table 1). The ability of treated surfaces to remain continuously active after repeated cleanings and use of liquid disinfectants is also critical (Figure 1). Unfortunately, there are no generally accepted methods for evaluating anti-viral surface coatings, making it difficult to compare the efficacy of different materials and studies. More research is warranted to better understand breadth of antiviral efficacy of these novel disinfecting technologies, and whether they can exact measurable and meaningful impacts on public health.

2. Continuously active disinfectants applied to hard, nonporous surfaces

A number of formulations have been developed and assessed over the past two decades that are capable of antiviral inactivation for extended periods of time following surface application (Table 2) [12–16]. Such applications have been considered as continuously active disinfectants and impart self-disinfecting properties to treated surfaces. There are many industry-based and third-party contract laboratory studies that have evaluated the antiviral properties of these surface treatments. However, few have been published to-date in peer-reviewed scientific journals [17], with an even smaller subgroup assessing efficacy against infectious viral agents. Continuously active disinfectants are generally evaluated for residual inactivation efficacy using a controlled, standardized wear and abrasion procedure such as that described in United States EPA Protocol #01-1A [18]. Briefly, a product applied to a hard non-porous surface is subjected to alternating dry and moistened wiping procedures over a specified time period (≥24 hours) with intermittent reinoculations of the test organism. A minimum of 12 wear cycles is required, and the remaining film of test product is challenged by a final dose of the target organism (≥4.8 log10) for up to 5 minutes of contact time. Residual efficacy depends in part on the amount of disinfectant remaining on the surface after the wear and abrasion testing which indicates its durability. Products that are readily removed from surfaces during repeated wet and dry wiping events could require regular reapplication to ensure proper performance against target microbes. As with standard disinfection,

| Coating* | Type of viruses tested against†‡ | Mechanism of inactivation |
|----------|----------------------------------|--------------------------|
| Silane polymer QAC | Influenza, HCoV-229E, SARS-CoV-2, feline calcivirus | Behaves as a surfactant; disrupts lipid and protein structure |
| Copper | Influenza A, hepatitis A, feline calcivirus, adenovirus, HCoV-229E, SARS-CoV2 | Reactive oxygen species; protein and nucleic acid denaturization |
| Silver | Influenza, SARS-CoV2, HCoV-229E, murine norovirus | Reaction with sulfhydryl groups in proteins; prevention of viral attachment to host cells |
| Zinc | Murine norovirus, SARS-CoV-2, influenza | Inhibiting proteolytic cleavage, preventing synthesis of viral polypeptides |
| Titanium dioxide | Influenza, adenovirus; SARS-CoV-2 | Generation of reactive hydroxyl radicals |

*QAC: quaternary ammonium compound.
†HCoV-229E: human coronavirus 229E.
‡SARS-CoV-2: SARS-related coronavirus 2.

Table 2.
Common antiviral surface chemistries and mechanisms of action [12–16].
residual effectiveness generally follows the hierarchy of susceptibility of viruses to disinfectants, where enveloped viruses are more susceptible to inactivation than non-enveloped viruses [19].

Quaternary ammonium compounds (QAC) have been in general use by industry and consumers for almost 70 years, mostly as rapid-action (≤ 10 minutes contact time) spray disinfectants for contaminated surfaces. They are considered as cationic surfactants or detergents, and are highly effective at disrupting the inner membranes of bacteria and lipid bilayers of enveloped viruses. QAC have undergone formulation changes to enhance effectiveness against non-enveloped viruses [20]. When combined with silane and polymers, they can be applied as a surface coating with antimicrobial properties [21]. Silane-QAC are long-chain molecules comprised of three principal components: 1) a silane base for covalent bonding to surfaces; 2) a centrally-located positively-charged nitrogen component, and 3) a long chain ‘spear’ consisting of a methyl hydrocarbon group. They can be applied to hard surfaces and to fabrics, and their virucidal efficacies may persist from 24 hours to weeks on treated surfaces.

Peer-reviewed studies evaluating the effectiveness of QAC-based surface coating treatments against viruses are currently limited. A quaternary ammonium polymer coating applied to stainless steel coupons demonstrated greater than 99.9% (>3 log₁₀) reduction during 2 hours of contact against SARS-CoV-2 and human coronavirus 229E in the presence of 5% organic soil, although wear testing was not performed to assess residual antiviral activity [22]. Another study evaluating a QAC applied onto acrylic surfaces against subsequent SARS-CoV-2 and human coronavirus 229E contamination events demonstrated rapid inactivation upon contact (>90% >1 log₁₀) reduction; however, just one cleaning event of the coating using a water-based detergent and microfiber cloth substantially reduced product efficacy [23]. More peer-reviewed research is needed to better understand the breadth of QAC coating efficacy against the spectrum of non-enveloped and enveloped viruses, and under varying soil load and environmental conditions. Additional studies are also warranted to assess the durability of these coatings following simulated touches and cleaning events, and the resulting impacts on antiviral effectiveness.

3. Titanium dioxide

Titanium dioxide (TiO₂) is a photocatalytic inorganic chemistry that can be applied to a wide variety of surface types to provide antiviral protection. It does not inactivate viruses directly, but acts as a catalyst in the presence of UVA light (wavelength 315 to 400 nm) to generate reactive oxygen species that cause structural damage to viruses. The presence of moisture (in the air or on the surface) and oxygen are necessary for TiO₂ to be an effective antiviral agent. Light intensity is also key in driving the photocatalytic reaction. Residual photocatalytic activity may also occur in the dark after exposure to UV light, but is dependent on the prior exposure intensity.

Most of the studies evaluating the antimicrobial effectiveness of TiO₂ have focused on bacteria, and data on viruses remains scant in the literature [16]. TiO₂ has demonstrated >3 log₁₀ reduction against influenza A within 4 hours, and >1 log₁₀ inactivation of feline calicivirus within 8 hours [24]. TiO₂ coatings have also been modified with fluorine to increase the production of reactive oxygen species under the low UVA-intensity fluorescent lighting that is typically found within indoor settings. Bacteriophage MS2, feline calicivirus, and murine norovirus infectivity levels were reduced by 2.6, 2.0, and 2.6 log₁₀ respectively, on fluorinated TiO₂.
Antiviral Coatings as Continuously Active Disinfectants
DOI: http://dx.doi.org/10.5772/intechopen.101752

surfaces [25]. The antiviral action of TiO$_2$ can be further enhanced within indoor environments by the addition of metals [26, 27]. A 1% silver-amended TiO$_2$ formulation yielded >4.00 log$_{10}$ reduction of influenza A and enterovirus following a 20-minute exposure in the presence of a low intensity (15 W) UVA lamp [28]. More recently, infectious SARS-CoV-2 was reduced to levels below detection on TiO$_2$ and TiO$_2$-Silver (Ag) ceramic-coated tiles within 5 hours of exposure [15].

4. Metals

Metals such as copper, silver, and gold have been recognized since ancient times as having some health benefits, and the antibacterial properties of metals have since been well-studied [29]. In contrast, the mechanisms of metal inactivation of specific viruses remain unclear, although a number have been proposed and evaluated. Certain metals in trace amounts are critical to the function of viral proteins and genetic processes; however, levels in excess cause structural damage and affect viability [14]. The presence of these metals stimulates the generation of reactive oxygen species and damages viral envelopes as well as nucleocapsid proteins [30]. Metals can be incorporated into plastics and fabrics, used as actives in coating formulations, and fashioned directly into surfaces for direct use (e.g., copper sheets for incorporation into high-touch surfaces).

4.1 Copper

The antimicrobial properties of copper have been extensively studied, with efficacy demonstrated over a broad range of temperature and humidity values [1]. The proposed antiviral mechanisms of solid-state copper, copper oxides, and copper alloys against enveloped and non-enveloped viruses have been thoroughly reviewed [31]. Copper (I), (II), (III) ions act directly by denaturing viral surface proteins, and indirectly by the formation of reactive oxygen species that damage viral RNA and DNA. Copper surfaces inactivated infectious influenza A (H1N1) within 6 hours by 3 to 4 log$_{10}$, relative to virus levels remaining on stainless steel coupons [32]. Although copper has demonstrated broad-spectrum antimicrobial activity, it may be impractical to replace bulk materials within high-traffic areas (e.g., clinical settings) with copper products or components. The recent development of cold- and thermally-applied copper sprays, as well as fixed copper nanoparticle coatings and paints, enables continuously active disinfection measures against a spectrum of viruses [16]. Copper nanoparticles in the oxide form have shown promise against herpes simplex virus, human norovirus, and influenza A (H1N1) [31]. When applied using the cold spray technique, copper nanoparticles reduced infectious influenza A virus particles to levels below detection within 10 minutes [33].

4.2 Silver

The antimicrobial properties of silver have been known for more than a century. Much of the research investigating the antimicrobial properties of silver has examined inactivation in suspension, where lower doses are required to achieve inactivation effects relative to other metals [34]. Silver binds with disulfide (S–S) and sulfhydryl (–SH) groups in proteins, facilitates the production of reactive oxygen species (e.g., free radicals), and is believed to inhibit entry of HIV-1 into CD4+ host cells [35]. Unlike copper, the efficacy of silver decreases markedly at relative humidity levels <20% [1], and solid-state silver appears to be much less effective against
bacteriophage Qβ and influenza A than solid-state copper [36]. For surface applications, silver nanoparticles have been extensively researched. Silver nitrate and silver nanoparticles in surface coatings reduced recoverable levels of feline calicivirus and murine norovirus for up to 150 days [37]. Silver has also been incorporated into fabrics (hospital gowns, pillowcases, cotton sheets), textiles, and membranes, demonstrating antiviral properties against feline calicivirus and murine norovirus, as well as enveloped viruses [16, 38].

4.3 Zinc

The antiviral properties of zinc have been researched for the past several decades. Zinc inhibits proteolytic cleavage and the synthesis of viral polypeptides by human rhinovirus [39], and interferes with polymerase function and protein production by herpes simplex virus 1 [16]. For surface applications, pure zinc, itself, does not exhibit high levels of antiviral activity. A 1 log_{10} reduction of murine norovirus on pure zinc was measured within 2 hours, relative to complete inactivation of the test virus via synergism when exposed to a copper-silver-zinc alloy [40]. On plastic coupons with incorporated silver/copper-zeolites, > 1.7 log_{10} and > 3.8 log_{10} reductions were achieved for human coronavirus 229E and feline calicivirus, respectively, within 24 hours [41]. More recently, zinc ion-embedded polyamide fibers were found to reduce levels of infectious influenza A and SARS-CoV-2 by approximately 2 log_{10} within 30 minutes [42].

5. Novel antiviral surface treatments

Research efforts are ongoing for the development of novel and continuously active coatings that are capable of maintaining low levels of bioburden while inactivating pathogenic microorganisms. A thorough review has been published of these coatings and their proposed mechanisms of action [14, 43]. The antiviral actives include biopolymers (e.g., antimicrobial peptides), synthetic polymers (e.g., polyethyleneimines, and graphene [14, 44, 45]. Natural product-based surface coatings and super-hydrophobic surfaces are also under development [46, 47]. Although many of these innovative technologies demonstrate promising antiviral effectiveness, further assessments of efficacy against additional types of viruses under various conditions are required. Reproducibility data generated among different lab groups would also be ideal to ensure product efficacy and reliability. Further, scaling up from the lab bench to assess these technologies under real-world conditions (i.e. placement into high-traffic, high-touch areas) will provide insight as to the consistency of their efficacy.

6. Conclusions and recommendations

From this review, it is clear that promising antiviral continuously active disinfectants are a reality. However, many obstacles exist before their widespread implementation. These include:

- Development and validation of standard methods for testing the efficacy of antiviral continuously active disinfectants. Ideally, these methods would indicate appropriate experimental conditions including relative humidity and temperature, organic soil load matrices, and evaluation of virucidal efficacy against enveloped and non-enveloped viruses.
• Establishing an acceptable contact time for a 3 log_{10} (99.9%) decrease in infectious virus. Some continuously active disinfectants can achieve this goal within a few minutes, and others may require 1 to 2 hours.

• Demonstration of the reduction in illnesses within facilities in which continuously active disinfectants are used. This is an ideal requirement, but difficult to achieve because of the high cost and multiple routes by which enteric and respiratory viruses can be transmitted. Reductions in hospital-acquired infections have been demonstrated with the use of copper [48–49] and silane QAC [50] disinfectants, but such studies are not always ideal because of limitations inherent in epidemiological studies, and extracting precision is usually lacking. Further, more information is needed as to the potential human health and environmental impacts of silane QAC usage in these settings.

• Application of quantitative microbial risk assessment (QMRA) to quantify the cost/benefits of continuously active disinfectants. QMRA is a lower-cost approach to documenting the probability of disease reduction that can be achieved. It can be used to estimate the difference in benefits from a continuously active disinfectant that inactivates 99.9% of the virus within 1 minute vs. one that achieves this within 2 hours.

• Education of regulators, public health officials, and the general public is necessary to ultimately achieve the benefits of continuously active disinfectants. There is concern that their use may provide a false sense of security, causing consumers to clean and disinfect less frequently. Continuously active disinfectants should be looked upon as an additional barrier, and not as a replacement for routine cleaning and disinfection.

Conflict of interest

The authors have no conflict of interest to declare.

Author details

Luisa A. Ikner* and Charles P. Gerba
Department of Environmental Science, The University of Arizona, Tucson, AZ, United States of America

*Address all correspondence to: ikner@arizona.edu

IntechOpen

© 2021 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
References

[1] Castaño N, Cordts S, Kurosu Jalil M, Zhang K, Kopppaka S, Bick A, et al. Fomite transmission, physicochemical origin of virus–surface interactions, and disinfection strategies for enveloped viruses with applications to SARS-CoV-2. ACS Omega. 2021;6:6509-6527. DOI: 10.1021/acsomega.0c06335

[2] Boone S, Gerba C. Significance of fomites in the spread of respiratory and enteric viral disease. Applied and Environmental Microbiology. 2007;73:1687-1696. DOI: 10.1128/AEM.02051-06

[3] Lopez G, Gerba C, Tamimi A, Kitajima M, Maxwell S, Rose J. Transfer efficiency of bacteria and viruses from porous and nonporous fomites to fingers under different relative humidity conditions. Applied and Environmental Microbiology. 2013;79:5728-5734. DOI: 10.1128/AEM.01030-13

[4] Julian T, Leckie J, Boehm A. Virus transfer between fingerpads and fomites. Journal of Applied Microbiology. 2010;109:1868-1874. DOI: 10.1111/j.1365-2672.2010.04814.x

[5] Nicas M, Best D. A study quantifying the hand-to-face contact rate and its potential application to predicting respiratory tract infection. Journal of Occupational and Environmental Hygiene. 2008;5:347-352. DOI: 10.1080/15459620802003896

[6] Rutala W, Kanamori H, Gergen M, Knelson L, Sickbert-Bennett E, Chen L, et al. CDC prevention epicenters program Enhanced disinfection leads to reduction of microbial contamination and a decrease in patient colonization and infection. Infection Control & Hospital Epidemiology. 2018;39:1118-1121. DOI: 10.1017/ice.2018.165

[7] Rutala W, Weber D. The benefits of surface disinfection. American Journal of Infection Control. 2004;32:226-231

[8] Kraay A, Hayashi M, Berendes D, Sobolik J, Leon J, Loopman B. Risk for fomite-mediated transmission of SARS-CoV-2 in child daycares, schools, and nursing homes, and offices. Emerging Infectious Diseases. 2021;27:1229-1231. DOI: 10.3201/eid2704.203631

[9] Weber D, Anderson D, Rutala W. The role of the surface environment in healthcare-associated infections. Current Opinion in Infectious Diseases. 2013;26:338-344. DOI: 10.1097/QCO.0b013e3283630f04

[10] Hardy K, Gossain S, Henderson N, Drugan C, Oppenheim B, Gao F, et al. Rapid recontamination with MRSA of the environment of an intensive care unit after decontamination with hydrogen peroxide vapour. Journal of Hospital Infection. 2007;66:360-368. DOI: 10.1016/j.jhin.2007.05.009

[11] The American Cleaning Institute. Cleaning and COVID-19: Survey Shows 42% not disinfecting properly [Internet]. 2020. Available from: https://www.cleaninginstitute.org/newsroom/releases/cleaning-and-covid-19-survey [Accessed: October 21, 2021]

[12] Kumari S, Chatterjee K. Biomaterials-based formulations and surfaces to combat viral infectious diseases. APL Bioengineering. 2021;5:011503. DOI: 10.1063/5.0029486

[13] Shirvanimoghaddam K, Skbari M, Yadav R, Al-Tamimi A, Naebe M. Fight against COVID-19: The case of antiviral surfaces. APL Materials. 2021;9:031112. DOI: 10.1063/5.0043009

[14] Rakowska P, Tiddia M, Faruqui N, Bankier C, Pei Y, Pollard A, et al. Antiviral surfaces and coatings and their mechanisms of action. Communications Materials. 2021;2:1-19. DOI: 10.1038/s43246-021-00153-y
Antiviral Coatings as Continuously Active Disinfectants
DOI: http://dx.doi.org/10.5772/intechopen.101752

[15] Miscohova P, Chadha A, Hesseloj T, Fraternali F, Ramsden J, Gupta R. Rapid inactivation of SARS-CoV-2 by titanium dioxide surface coating. Wellcome Open Research. 2021;6:56. DOI: 10.12688/wellcomeopenres.16577.1

[16] Imani S, Ladouceur L, Marshall T, Maclachlan R, Soleymani L, Didar T. Antimicrobial nanomaterials and coatings: Current mechanisms and future perspectives to control the spread of viruses including SARS-CoV-2. ACS Nano. 2020;14:12341-12369. DOI: 10.1021/acsnano.0c05937

[17] Rutala W, Gergen W, Sickbert-Bennett E, Anderson D, Weber D. Antimicrobial activity of a continuously active disinfectant against healthcare pathogens. Infection Control & Hospital Epidemiology. 2019;40:1284-1286. DOI: 10.1017/ice.2019.260

[18] United States Environmental Protection Agency. Protocol for Residual Self-Sanitizing Activity of Dried Chemical Residues on Hard, Non-Porous Surfaces: #01-1A. Washington D.C., United States: United States Environmental Protection Agency. 2015. Available from: https://www.epa.gov/sites/production/files/2015-09/documents/cloroxpcol_final.pdf [Accessed: February 16, 2016]

[19] Sattar S. Hierarchy of susceptibility of viruses to environmental surface disinfectants: A predictor of activity against new and emerging viral pathogens. Journal of AOAC International. 2007;90:1655-1658. DOI: 10.1093/jaoac/90.6.1655

[20] Gerba C. Quaternary ammonium biocides: Efficacy in application. Applied and Environmental Microbiology. 2015;81:464-469. DOI: 10.1128/AEM.02633-14

[21] McDonnell G. Antisepsis, Disinfection and Sterilization. 2nd ed. Washington, DC: ASM Press; 2017. p. 410

[22] Ikner L, Torrey J, Gundy P, Gerba C. Efficacy of an antiviral surface coating against human coronavirus 229E and SARS-CoV-2. American Journal of Infection Control. 2021;49(12):1569-1571. DOI: 10.1016/j.ajic.2021.08.031

[23] Butot S, Baert L, Zuber S. Assessment of antiviral coatings for high-touch surfaces by using human coronaviruses HCoV-229E and SARS-CoV-2. Applied and Environmental Microbiology. 2021;87:e01098-e01021. DOI: 10.1128/AEM.01098-21

[24] Nakano R, Hara M, Ishiguro H, Yao Y, Ochiai T, Nakata K, et al. Broad spectrum microbicidal activity of photocatalysis by TiO2. Catalysts. 2013;3:310-323. DOI: 10.3390/catal3010310

[25] Park G, Cho M, Cates E, Lee D, Oh B, Vinjé J, et al. Fluorinated TiO2 as an ambient light-activated virucidal surface coating material for the control of human norovirus. Journal of Photochemistry and Photobiology B: Biology. 2014;140:315-320. DOI: 10.1016/j.jphotobiol.2014.08.009

[26] Miyauchi M, Sunada K, Hashimoto K. Antiviral effect of visible light-sensitive Cu(II)-TiO2 photocatalyst. Catalysts. 2020;10:1093. DOI: 10.3390/catal10091093

[27] Moongraksathum B, Chien M, Chen Y. Antiviral and antibacterial effects of silver-doped TiO2 prepared by the peroxo sol-gel method. Journal of Nanoscience and Nanotechnology. 2019;19:7356-7362. DOI: 10.1166/jnn.2019.16615

[28] Liu M, Sunada K, Miyauchi HK. Visible-light sensitive Cu(II)-TiO2 with sustained anti-viral activity for efficient indoor environmental remediation. Journal of Materials Chemistry A. 2015;3:17312-17319. DOI: 10.1039/CST03756E
Disinfection of Viruses

[29] Lemire J, Harrison J, Turner R. Antimicrobial activity of metals: Mechanisms, molecular targets and applications. Nature Reviews Microbiology. 2013;11:371-384. DOI: 10.1038/nrmicro3028

[30] Sunada K, Minoshima M, Hashimoto K. Highly efficient antiviral and antibacterial activities of solid-state cuprous compounds. Journal of Hazardous Materials. 2021;235:265-270. DOI: 10.1016/j.jhazmat.2012.07.052

[31] Govind V, Bharadwaj S, Sai Ganesh M, Vishnu J, Shankar K, Shankar B, et al. Antiviral properties of copper and its alloys to inactivate covid-19 virus: A review. Biometals. 2021;34:1-19. DOI: 10.1007/s10534-021-00339-4

[32] Noyce J, Michels H, Keevil C. Inactivation of influenza A virus on copper versus stainless steel surfaces. Applied and Environmental Microbiology. 2007;73:2748-2750. DOI: 10.1128/AEM.01139-06

[33] Champagne V, Sundberg K, Helfricht D. Kinetically deposited copper antimicrobial surfaces. Coatings. 2019;9:257. DOI: 10.3390/coatings9040257

[34] Silvestry-Rodriguez N, Sicarios-Ruelas K, Gerba C, Bright K. Silver as a disinfectant. Reviews of Environmental Contamination and Toxicology. 2007;191:23-45. DOI: 10.1007/978-0-387-69163-3_2

[35] Lara H, Ayala-Nuñez N, Ixtepan-Torrent L, Rodriguez-Padilla C. Mode of antimicrobial action of silver nanoparticles against HIV-1. Journal of Nanobiotechnology. 2010;8:1-10. DOI: 10.1186/1477-3155-8-1

[36] Minoshima M, Lu Y, Kimura T, Nakano R, Ishiguro H, Kubota Y, et al. Comparison of the antiviral effect of solid-state copper and silver compounds. Journal of Hazardous Materials. 2016;312:1-7. DOI: 10.1016/j.jhazmat.2016.03.023

[37] Castro-Mayorga J, Randazzo W, Fabra M, Lagaron J, Aznar R, Sanchez G. Antiviral properties of silver nanoparticles against norovirus surrogates and their efficacy in coated polyhyroxylanoates systems. LWT – Food Science and Technology. 2017;79:503-510. DOI: 10.1016/j.lwt.2017.01.065

[38] Gerba C, Sifuentes L, Lopez G, Abd-Elmaksound S, Calabrese J, Tanner B. Wide-spectrum activity of a silver-impregnated fabric. American Journal of Infection Control. 2016;44:689-690. DOI: 10.1016/j.ajic.2015.11.033

[39] Korant B, Kauer J, Butterworth B. Zinc ions inhibit replication of rhinoviruses. Nature. 1974;248:588-590. DOI: 10.1038/248588a0

[40] Warnes S, Summersgill E, Keevil C. Inactivation of murine norovirus on a range of copper surfaces is accomplished by a loss of capsid integrity. Applied and Environmental Microbiology. 2015;81:1085-1091. DOI: 10.1128/AEM.03280-14

[41] Bright K, Sicarios-Ruelas E, Gundy P, Gerba C. Assessment of the antiviral properties of zeolites containing metal ions. Food and Environmental Virology. 2008;1:37-41. DOI: 10.1007/s12560-008-9006-1

[42] Gopal V, Nilsson-Payant B, French H, Siegers J, Yung W, Hardwick M, et al. Zinc-embedded polyamide fabrics inactivate SARS-CoV-2 and influenza A virus. ACS Applied Materials & Interfaces. 2021;13:30317-30325. DOI: 10.1021/acsami.1c04412

[43] Bäumler W, Eckl D, Holzmann T, Schneider-Brachert W. Antimicrobial
coatings for environmental surfaces in hospitals: A potential new pillar for prevention strategies in hygiene. Critical Reviews in Microbiology. 2021:1–35. DOI: 10.1080/1040841X.2021.1991271

[44] Reina G, Iglesias D, Samori P, Bianco A. Graphene: A disruptive opportunity for COVID-19 and future pandemics? Advanced Materials. 2021;33:2007847. DOI: 10.1002/adma.202007847

[45] Basak S, Packirisamy G. Nano-based antiviral coatings to combat viral infections. Nano-Structures & Nano-Objects. 2020;24:100620. DOI: 10.1016/j.nanoso.2020.100620

[46] Chauhan P, Kumar A. Development of a microbial coating for cellulosic surface using aloe vera and silane. Carbohydrate Polymer Technologies and Applications. 2020;1:100015. DOI: 10.1016/j.carpta.2020.100015

[47] Elzaabalawy A, Meguid S. Potential of combating transmission of COVID-19 using novel self-cleaning superhydrophobic surfaces: Part II—thermal, chemical, and mechanical durability. International Journal of Mechanics and Materials in Design. 2020;16:433-441. DOI: 10.1007/s10999-020-09512-y

[48] Michels H, Keevil C, Salgado C, Schmidt M. From laboratory research to a clinical trial: Copper alloy surfaces kill bacteria and reduce hospital-acquired infections. HERD: Health Environments Research & Design Journal. 2015;9:64-79. DOI: 10.1177/1937586715592650

[49] Salgado C, Sepkowitz K, John J, Cantey J, Attaway H, Freeman K, et al. Copper surfaces reduce the rate of healthcare-acquired infections in the intensive care unit. Infection Control & Hospital Epidemiology. 2013;34:479-486. DOI: 10.1086/670207

[50] Ellingson K, Pogreba-Brown K, Gerba C, Elliott S. Impact of a novel antimicrobial surface coating on healthcare–associated infections and environmental bioburden at 2 urban hospitals. Clinical Infectious Diseases. 2020;71:1807-1813. DOI: 10.1093/cid/ciz1077