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Prevention of Fomite Transmission of SARS-CoV-2 with Copper Cold Spray Coatings

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Abstract

This review article contextualizes the way in which the antipathogenic properties and antimicrobial contact killing/ inactivating performance of copper cold spray coatings and consolidated material surfaces can be extended to the COVID-19 pandemic as a preventative measure. Specifically, literature is reviewed in terms of how copper cold spray coatings can be applied to high-touch surfaces in biomedical as well as healthcare settings to prevent fomite transmission of SARS-CoV-2 through rapidly inactivating SARS-CoV-2 virions after infecting a surface. After providing an introduction that encapsulates a brief history of self-sanitizing surfaces and surface sterilization, a number of alternative antimicrobial coatings and materials that do not rely upon the oligodynamic properties of copper are detailed. Given the ongoing need for recognition of said alternative antimicrobial materials by authoritative agencies, such as the EPA, the relevant literature on copper-based antipathogenic coatings and surfaces are then detailed. Thereafter, a comprehensive take on antimicrobial copper cold spray coatings is provided. Particular attention is then given to the unique microstructurally mediated pathway of copper ion diffusion associated with copper cold spray coatings that enable fomite inactivation. This review is then concluded by way of situating the literature reviewed and the implications ascertained through such an analysis of the literature in terms of COVID-19 and how copper cold sprayed coatings can be readily utilized as a preventative measure against fomite transmission of SARS-CoV-2.

Keywords

Antiviral materials; Contact killing or inactivating surfaces; Antimicrobial coatings; Copper; Cold spray; COVID-19; SARS-CoV-2; Antipathogenic coatings

Introduction

The tendency of a microbe to remain active on a given surface has been of concern to the scientific research community since Leuwenhook communicated his discovery of microorganisms, as well as his observation of their sensitivity to vinegar exposure, in the 1670's [1]. Since the time of Leuwenhook, an overwhelming amount of information has been amassed in relation to surface sanitation and antimicrobial surfaces. Approximately 200 years after Leuwenhook's discoveries, phenolic antiseptic disinfectants were introduced in surgical settings for the sterilization of equipment after Lister'sresearch and development of functionalized phenolic agents in the 1880's [2]. Thereafter, in 1935, quaternary ammonium compounds were formally recognized as a bacterial disinfectant and one such commercial compound known as benzalkonium chloride was identified as being very successful as a medium for disinfecting surfaces in surgical settings as well [3]. Today, the Center for Disease Control and Prevention (CDC) in the U.S., as well as the Environmental Protection Agency (EPA), have recognized numerable surface disinfectants for use in healthcare settings.

The use of surface disinfecting agents for sterilization and sanitation relies upon the active engagement of healthcare workers and the tendency of healthcare workers to properly adhere to the instructions associated with a given disinfectant. One way to ensure that high-touch surfaces in medical environments are less likely to act as disease transmission and infection vectors is to not only apply sanitizing products with notable regularity, but to also utilize materials that are self-sanitizing to produce medical equipment and hardware and to apply antimicrobial coatings to legacy components and surfaces. Regardless of whether or not a coating is applied, or hospital grade hardware and equipment are redesigned using fast-acting antipathogenic base materials, one must understand what makes a material antimicrobial to begin with. Just as sterilizing and disinfecting agents experienced relatively rapid adoption and development after Lister introduced functionalized phenolic agents to the medical sector, notable progress has been made surrounding the underlying physics and chemistry associated with self-sanitizing materials.

Antimicrobial self-sanitizing surfaces have been investigated through the lens of a wide array of potential contact bacterial killing and viral inactivating mechanisms as well as various material categories. In so far as the metallurgical community is concerned, bio-based researchers have invoked oligodynamic action, first observed in the late 1800's by Nägeli [4], as a quintessential property of antimicrobial metallic systems. Although each elemental metal that may be considered oligodynamic achieve different degrees of antimicrobial efficacy relative to one another, aluminum, antimony, arsenic, barium, bismuth, boron, copper, gold, lead, mercury, nickel, silver, thallium, tin, and zinc, have all been identified as oligodynamic in one fashion or another. That being said, the exact way in which the oligodynamic capacity of the elemental metals listed can be harnessed are not universal. For example, when aluminum is in the form of aluminum acetate, the aluminum acetate compound/solution may be used as an antiseptic [5]. However, when an aluminum alloy is utilized as a material in a health care setting, pathogens are known to accumulate and remain active for significant periods of time on the aluminum surface.

With the aforementioned in mind, the elemental metal that is the most oligodynamic is copper. Still, just as aluminum's oligodynamic ability was shown to be sensitive to its form or condition, commercially pure elemental copper has been shown to yield a greater antimicrobial efficacy than bronze, which is a copper-based alloy [6].

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needed to reliably develop antimicrobial functional surfaces. As a result, almost all of the EPA approved surfaces are required to contain at least 60% copper content, which would include modern bronze alloys, which consist of 88% copper. Even though the principle of 60% copper content has been recognized by the EPA, the rate of surface self-sanitization, or contact bacterial killing or viral inactivation efficacy, of a copper-based material will vary as function of the material's composition, microstructure, and condition, among other relevant features such as surface roughness. Therefore, consideration must be given to the contact killing or inactivating rates associated with copper-based material options to ensure that copper coated hardware in a medical setting is able to self-sanitize as quickly as possible to minimize the window of time wherein fomite transmission may still occur.

Consequently, the objective of this review article is to situate the way in which the antipathogenic properties and antimicrobial contact killing or inactivating performance of copper cold spray coatings and consolidated material surfaces can be extended to the COVID-19 pandemicasa preventative measure. Specifically, literature is reviewed in terms of how copper cold spray coatings can be applied to high-touch surfaces in biomedical as well as healthcare settings to prevent fomite transmission of SARS-CoV-2 through rapidly inactivating SARS-CoV-2 virions after infecting a surface.

Alternative Antimicrobial Materials and Coatings

Due to the need for bactericidal and antipathogenic agents, in light of antibiotic resistance as well as the occurrence of viral outbreaks, such as the global SARS-CoV-2 pandemic, alternative antimicrobial coatings other than copper cold sprayed surfaces that are widespread and presently achieving degrees of viability are discussed next. Silver-doped $Mg_3(PO_4)_2.xH_2O$ nanosheets have been coated onto spinal implantation materials in [7], whereas nanostructured glycan architecture has been advanced as an antiviral material with respect the known as H1N1 [8], In addition to the virus briefly mentioned silver-doped nanosheets, noteworthy antipathogenic coatings and materials that also have been studied as prospective bio-functional materials include titanium dioxide and silver composite films, TiCaPCON films with embedded zinc, platinum and/or silver, NO_x emitting coatings, graphene nanoplatelets, cross-linked ionic polymer coatings, alongside a number of additional methods. While motivated by the preventative public health benefits, such creative and novel approaches to tackling fomite transmission of pathogens likely stems from the potential profit margins as well. That is, such research and development was also likely inspired by economic forecasts suggesting that the market for antipathogenic coatings was believed to reach more than eight billion USD by 2025.

With such economic incentives in mind, one need not be surprised by the fact that unorthodox coating systems have been remarked upon within the relevant literature. Although the aforementioned methods are clearly unique and innovative, most if not all of those listed above have not been recognized by relevant regulatory agencies as being reliably antipathogenic. On the other hand, an overwhelming effort led by the EPA offered researchers the scaffolding needed to reliably develop antimicrobial functional surfaces. That is, almost all of the U.S. EPA approved surfaces are required to contain at least 60% copper content. Since the majority of the alternative antimicrobial materials and coatings of interest and detailed in this section of the manuscript do not use copper in accordance with the EPA, alternative antipathogenic copper surfaces are discussed next.

Antipathogenic Copper Surfaces

The number of ways in which antimicrobial copper-containing materials may be produced and fabricated are wide ranging. Given the numerable means of production, a number of relatively recent studies are contextualized with respect to the current landscape of antipathogenic copper surfaces published to date. Subsequently, a brief overview of SARS-CoV-2 tested copper-based materials published during the COVID-19 pandemic are highlighted before the article transitions to antimicrobial copper cold spray in particular. In the meantime, Haider et al. demonstrated dual to compatibility and antimicrobial behavior of copper-oxide containing hybrid nano fiber scaffoldings that were procured using electrospinning techniques in [9]. Two studies by Villapun et al. focused upon copper-based antimicrobial coatings achieved through bulk metallic glass composites in [10] and [11]. Ciacotich et al. analyzed the "antibacterial activity of a copper-silver alloy" in a 2019 study published in *Global Challenges* [12], while Kocaman and Keles characterized the antibacterial efficacy of copper coatings using a wire arc spray deposition process after exposure to various bacterial pathogens [13]. While discussion could continue, the final copper-containing approach that will be noted herein before transitioning to SARS-CoV-2 contact inactivation concerns the work of Muralidharan et al. More to the point, a sulphonated poly-(ether ether ketone)-copper film for antimicrobial applications was detailed in *Materials Today Communications* in 2020 [14].

Another recent work of scholarship was released on a pre-print server which documented the use of Luminore CopperTouch™ coatings to inactivate SARS-CoV-2 on coated surfaces as detailed [15]. Unfortunately, the research by Mantlo et al., does not appear to delve into the realm of mechanisms associated with copper- mediated contact inactivation of SARS-CoV-2 [15]. Regardless, the Luminore CopperTouch™ surface was found to inactivate 99% of the SARS CoV-2 titers within two hours while also inactivating 99.9% of the Ebola as well as Marburg viruses in that period of time as well. Consistent with our own claim that cuprous oxide (Cu_2O) is likely to be just as effective as pure copper in diffusing the copper ions need for viral contact inactivation [16], in agreement with [17] too, recent work undertaken at Virginia Tech has identified another copper-based coating that can also rapidly inactivate SARS- CoV-2 too [18]. Still, one of the most promising aspects of copper cold spray antipathogenic coatings relative to the coatings presented by Behzadinasab et al. and Mantlo et al. is the likelihood of even greater inactivation rates below one-hour of exposure time given the dynamically recrystallized and severely plasticly deformed microstructure, which greatly enhances iondiffusivity.

Antimicrobial Copper Cold Spray

In 2013, Champagne and Helfritch explored the utility of three copper-based antimicrobial coatings or antimicrobial copper surfaces using three different thermal spray deposition methods [19]. The three copper coatings generated by Champagne and Helfritch were produced using the plasma spray process, the arc spray process, and the cold spray materials consolidation process, respectively. Each of the three coatings were deposited upon an aluminum substrate, which was comparable to the type of aluminum alloys used to manufacture hardware commonly found in hospital-like settings, until the

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coatings reached a thickness of about 1 mm. Upon inspecting the microstructures of the three coatings produced using plasma spray, arc spray, and cold spray, Champagne and Helfritch noted that variations "in microstructure are clearly evident, suggesting that differences in biological activity mayalso occur," [19]. After procuring each of the three types of thermal spray coatings, methicillin-resistant *Staphylococcus Aureus* (MRSA) was inoculated and studied in accordance with a procedure titled "Test Method for Efficacy of Copper Alloy Surfaces as a Sanitizer," which is an EPA protocol of relevance. Ultimately, the resultant percent of surviving MRSA after two hours of exposure time to the three thermal spray copper coatings was consistent with their assertion that differences in biological activity would follow from the differences in microstructures associated with each surface. While the plasma sprayed surface killed less than 90% of the exposed MRSA after two hours, the cold sprayed copper killed more than 99.999% of the bacterial agent after the same duration of time [19].

Even though copper is clearly the antipathogenic metal of significant interest and relevance herein, it is also worth noting that antibacterial and antimicrobial coatings have been reported upon using non-pure copper cold spray as well. For more information surrounding such non-pure copper-based approaches that still used cold spray as the means of producing the bio-functional antimicrobial surfaces, the reader ought to consider the subsection of Vilardell et al.'s 2015 review article[20], titled "Antibacterial/antimicrobial coatings." Assuming that Vilardell et al.'sreview was thorough enough to capture a majority of the antimicrobial applications and related uses of cold spray deposition prior to writing their manuscript, a brief survey of the resultant works of scholarship reported upon since 2015/2016 reveals continued consideration of antimicrobial copper-containing cold spray. Rutkowska-Gorczyca investigated the microstructure of an antibacterial copper and titanium dioxide composite coatings produced using low pressure cold spray, rather than the more commonly employed high pressure cold spray apparatus, [21]. Prior to the work by Rutkowska-Gorczyca, Sanpo et al. analyzed a copper and zinc oxide composite cold spray coating for the purpose of contact killing and prohibiting *Cobetia marina* bacterial attachment to maritime vessels [22].

Beyond the work cited, which was performed by Sanpo et al. [22], there is, in general, a growing body of evidence that direct surface contact plays an important role in the antimicrobial activity of copper surfaces. Such evidence is two-fold. Topographies have been shown to influence antipathogenic performance alongside surface energetics and surface chemistry. Vucko et al. demonstrated the antifouling capacities of high-density polyethylene "[metalized] with copper powder using cold spray" [23], finding that "[after] 250 days in the field, Cu-embedded HDPE… [was] completely free of hard foulers." The embedment of a biocidal anti-biofoulingagent, i.e., copper, demonstrates how microbial agents achieved limited success in adhering to the metalized surface while also experiencing stunted proliferation. From the vantage point of the medical as well as food-based economic sectors, El-Eskandrany et al. explored the use of a copper-based ($Cu_{50}Ti_{20}Ni_{30}$) alloyed metallic glass powder feedstock for antibacterial cold spray application in El-Eskandrany et al. [24].

Given the objective as well as scope of this article, the final set of antimicrobial copper-based cold spray papers that will be discussed next concern additional work by Champagne and coauthors, work by da Silva et al. [25], and work by the authors of the current manuscript. Following the 2013 article by Champagne and Helfritch, the two authors partnered with Sundberg et al. in 2015 to investigate the ability of copper cold spray coatings to inactivate the viral pathogen known as Influenza A. Said work was pursued in an attempt to showcase copper cold spray coatings' capacity to prevent fomite transmission of a viral infectious agent, having already achieved demonstrable antibacterial performance with respect to MRSA in 2013. Influenza A was selected due to the fact that fomite transmission can occur up to three full days after a regular surface becomes contaminated. At the same time, Sundberg et al. varied the copper powder feedstocks to achieve commercially pure copper cold sprayed coatings that housed the same microstructure observed in 2013 and another that was nanostructured. Interestingly, the nanostructured copper cold sprayed surface achieved a 99.3% reduction of active Influenza A fomites after two hours of exposure. In comparison with the nanostructured cold spray coating, the conventional copper cold spray coating used in the 2013 study was found to achieve a 97.7% reduction of active Influenza A fomites. Another observation worth noting is the fact that even when the conventional feedstock powder was varied two additional times (in terms of powder supplier, etc.), the percent reduction of MRSA after two hours of exposure was consistent with the 2013 study, reaching > 99.9%.

Under the tutelage of Dr.Cote (one of the coauthors of the present manuscript), Sundberg presented preliminary experimental work showing that several material properties influence antimicrobial efficacy and contact kill or inactivation rates in a doctoral dissertation, titled "Application of Materials Characterization, Efficacy Testing, and Modelling Methods on Copper Cold Spray Coatings for Optimized Antimicrobial Properties," [26]. Thereafter, Champagne et al. continued their analysis by way of summarizing their research to date in an attempt to substantiate their hypothesis that the dislocation density generated by cold spray deposition of copper particulates is the microstructural constituent responsible for the enhanced antimicrobial performance [27]. As will be discussed in the next section of the present article, their "application-dependent mechanism for antimicrobial effectiveness" has recently received notable intellectual resistance [16]. In other words, in 2019, Champagne, Sundberg and Helfritch reported dislocation density as the microstructural feature most responsible for enhanced antipathogenic contact killing or inactivation [27]. However, in 2020, the authors of this paper presented an alternative analytical framework that identified the concentration of grain boundaries present within a given surface area of the deposited material as being more deterministic of the coatings' antipathogenic performance than that of the dislocation density. Yet, rather than removing dislocation density from an expression for the effective copper ion diffusivity, the contribution of each respective term was weighted against one another, demonstrating the fact "that the grain boundary contribution to the effective diffusivity of copper ions in the nanostructured material outperforms the diffusivity of dislocation pipe diffusion by an order of magnitude," [16].

Though the microstructure-mediated fomite inactivation mechanism we have proposed in [16] and [28], will be the materials property category focused upon in the next section of the present article, additional work by the current coauthors on antipathogenic copper cold spray coatings will be described first. In 2019, we analyzed the nano-scale and micro-scale surface roughness of the conventional copper cold spray coatings produced using gas-atomized feedstock powder as well as the nanostructured copper cold spray coating produced using spray-dried feedstock powder [29].

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Such analysis was performed using atomic force microscopy (AFM) methods as well as 3D confocal microscopy to better understand the increased antiviral efficacy associated with the nanostructured copper cold spray coating relative to other copper-based materials and conventional copper cold spray coating. Coupling AFM with confocal microscopy-based characterization, we were better able to probe prospective surface-related mechanisms underlying the viricidal behavior of the cold spray material consolidations. In 2019, Sundberg et al., alongside the authors of this manuscript, attempted to supplement their work with corrosion studies to investigate chemical copper ion reactivities associated with the conventional and nanostructured cold spray coatings [30].

Concerning copper-oxide speciation at the surface, different oxides (Cu_2O and CuO) have been shown to influence the antimicrobial efficacy of antipathogenic copper contact killing or inactivating coatings in several ways. The surface oxide species has been shown to influence the copper ion species released from the coating via atomic diffusion, which react with pathogens. Cu^{1+} ions are currently thought to be more biocidal or viricidal than that of Cu^{2+}. This is in part due to the enhanced chemical stability of Cu^{2+} in solution when compared with Cu^{1+}. Also, Cu_2O yields a greater overall copper ion release rate than that of CuO [31]. Through the use of X-ray photoelectron spectroscopy (XPS), the present authors characterized the surface oxides of conventional and nanostructured copper cold sprayed coatings. Cu^{2+} was found to dominate the spectra associated with the conventional copper cold spray coating, whereas Cu^{1+} was found to dominate the spectra for the nanostructured copper cold spray coating, which is consistent with the increased antipathogenic efficacy associated with the nanostructured copper cold spray coating versus the conventional copper cold spray coating.

Microstructure Mediated Fomite Inactivation

Regardless of whether or not genomic RNA or nucleoprotein damage, membrane or membrane protein damage, reactive oxygen species [32] or copper ion speciation is the dominant pathway attributable to viral copper contact inactivation, the microstructural as well as physical properties we have reported upon maintains a significant role within each. In so far as the unique properties of copper cold spray coatings are concerned, Champagne et al. originally attributed the increased antipathogenic efficacy to the fact that the cold spray process leads to "extreme work hardening and correspondingly high dislocation density within the deposit… and ionic diffusion occurs principally through these dislocations…" in [19]. Subsequent work was shown to tentatively support the hypothesis provided by Champagne et al., through the use of a relation between hardness and dislocation density, such that higher hardness's were entertained as an indicator of increased antipathogenic performance for cold spray copper surfaces [33]. However, in 2019 and 2020, we began to further analyze the microstructures of antipathogenic copper cold sprayed materials to investigate the suitability of Champagne et al.'s dislocation driven copper ion diffusion framework for assessing the increased contact killing and inactivation rates for both viral and microbial pathogens relative to non-cold spray materials. As a result, the most current assessment and research published in the journal *Crystals* provides readers with a detailed look into the role such material defects, i.e., dislocations, maintain relative to the role of grain-boundary mediated copper ion diffusion[16].

Computational tools and high-resolution transmission electron microscopy are two of the essential platforms for materials design and development. Because of the fact that two competing dominant pathways responsible for the antipathogenic performance of copper cold spray coatings as a function of atomic copper ion diffusivity *via* dislocations versus grain boundaries, continued inspection must performed to confirm which of the two are truly more dominant. Such continued research must be performed in order to provide materials engineers with a desirable microstructural constituent or feature that ought to be targeted and promoted during manufacturing and processing to achieve maximal antipathogenic performance for optimized SARS-CoV-2 contact inactivation in the most critical biomedical and societal settings.

Since performing high-resolution microscopy is not a trivial task, historically speaking, the computational approach that was just alluded to has empowered researchers to develop microstructural diffusivity models for a given material. Accordingly, a number of studies have since emerged that demonstrate greater diffusion along grain boundaries relative to dislocations, suggesting that the grain boundary-mediated pathway ought to be of interest to those pursuing the implementation of copper cold spray coatings as a preventative measure in response to COVID-19. That being said, the assertion that focus and optimization ought to be prescribed to grain boundaries within a viricidal copper cold spray coating does not mean that materials processing engineers and bio-metallurgists alike should disregard the role dislocations can play. Through a synergistic approach that retains the maximally optimized surface area fraction concentration of highly disordered grain boundaries with an increased number of dislocations within a copper cold spray coating, one may be able to achieve a compounded or enhanced rate of atomic diffusion. On the other hand, such synergy should not be pursued at the expense of sacrificing the grain boundary concentration nor should such a compounded effect be pursued if the dislocations take on a detrimental form with respect to diffusivity. Nevertheless, some work has been done attesting to the fact that dislocations, in general, will enhance diffusivity regardless of being a screw or an edge dislocation form, for example, relative to the bulk diffusivity of defect free copper.

The microstructural insights already reported upon will be explored in even greater detail in the near future. In the meantime, we may also consider other relevant works of scholarship too. Recent research has been published in support of dislocation-driven and line-defect-dominated copper ion diffusion as the microstructural constituent responsible for pathogen contact killing or inactivation [34]. However, their work did not explicitly consider the grain size as a prospective driving force for ion diffusion, which would have attested to the area-fraction-containing grain boundaries, in relation to increased antipathogenic activity. Instead, they used X-ray diffraction (XRD) derived dislocation density as the structural property responsible for increased ion diffusion, even though the crystallite size was also shown to decrease concomitantly with the increase in dislocation density.

Though our earlier work focused upon the EPA-benchmark of two hours of pathogen exposure to a surface, self-sanitizing copper cold spray coatings produced by da Silva et al. found that 100% of the *Staphylococcus aureus* bacteria studied and exposed to the consolidated copper cold spray material were killed and/or "completely inhibited after 10 [minutes] of direct contact between the bacteria and the coating surface" [25]. Considering the fact that the nanostructured copper cold spray coatings we have developed and studied to date outperforms conventional copper cold spray coatings too, in terms of contact killing and inactivation efficacy associated with MRSA and Influenza A, among others, we anticipate near complete killing or inactivation on the order of minutes as well. More to the point, we anticipate that near complete inactivation or killing would have likely followed at periods of time less than the two-hour benchmark from the EPA if such time periods had been studied too.

Copper Cold Spray and COVID-19

Given the successful inactivation of the Influenza A virus after two hours of exposure to copper cold spray surfaces, as well asrecent research demonstrating that SARS-CoV-2 is no longer viable after exposure to copper-based material that wasn't as viricidal as our copper cold sprayed surfaces for four hours, we hypothesize that copper cold spray coatings could quickly be developed and deployed as a targeted mitigation strategy in response to the current COVID-19 pandemic. Moreover, the benefits gained by way of deploying antipathogenic copper cold spray surfaces in the fight against SARS-CoV-2 would also continue to provide ongoing security and mitigation of future pandemics through the prevention of fomite transmission from these surfaces.

Even though we now know that contact transmission "isn't thought to be the main way the virus [SARS-CoV-2] spreads," the CDC recognized the fact that "it may be possible that a person can get COVID-19 by touching a surface or object that has the virus [SARS-CoV-2] on it and then touching their own mouth, nose, or possibly their eyes" according to a clarification issued by the CDC in May 2020 [35]. Research published by Han and Yang, before the CDC press release was made publicly available, also substantiated the need for contact inactivating surfaces in medical as well as high-touch contact containing environments as a preventable measure in the fight against SARS-CoV-2 [36]. Han and Yang stated that "SARS-CoV-2 can be transmitted by droplets and contact. A study in South Korea showed that many environmental surfaces of patients with MERS were contaminated by MERS-CoV, and virus RNA was detected from environmental surfaces within 5 days after the last positive PCR of patients' respiratory samples," [36]. In fact, the World Health Organization released a scientific briefing on 09 July 2020, after the CDC press release as well as the Han and Yang paper, that attested to the veracity associated with contact-mediated transmission of the SARS-CoV-2 virus responsible for the ongoing COVID-19 public health crisis and global pandemic[37].

Nursing homes, medical facilities, public transportation, and schools have become high traffic focal points for the spread and transmission of the SARS-CoV-2 virus during the current pandemic. Such settings house a significant volume of high touch surfaces on which the SARS-CoV-2 virus has been shown to be able to remain active and transmissible. By way of refitting the high touch surfaces of the most vulnerable locations and organizations with such antiviral copper cold spray coatings, our functionalized coatings would be able to contribute to the mitigation and prevention of SARS-CoV-2 infection.

Different copper coating methods achieve varying disinfection rates despite employing the same feedstock material, compositionally speaking. We have demonstrated the fact that copper coatings deposited on a surface *via* cold spray kill or inactivate bacterial and viral pathogens with extreme rapidity. Cold spray is a versatile coating process that is particularly well suited for coating hospital equipment and touch surfaces. Our work has showcased the noteworthy anti-pathogenic properties of copper cold sprayed surfaces against Influenza A, MRSA, and *Pseudomonas aeruginosa*. Given the successful inactivation of more than 97% of the Influenza A virus after two hours of exposure to conventional copper cold spray surfaces and 99.3% after two hours of exposure to a nanostructured copper cold spray surface, as well as recent research demonstrating that SARS-CoV-2 is no longer viable after exposure to non-cold spray copper for four hours, we believe that copper cold spray could quickly be developed and deployed as a targeted mitigation strategy in response the current COVID-19 pandemic.

According to an article published in *The New England Journal of Medicine*, researchers verified that SARS-CoV-2 was no longer viable after being exposed to copper for four hours when a 99.9% commercially pure wrought copper sheet was utilized [38]. The EPA has acknowledged and certified a variety of copper-based materials as being antimicrobial and contact killing or inactivating surfaces that contain no more than 40% non-copper alloying elements. Yet, as we have discussed, the alloying chemistry, manufacturing method utilized, and materials processing applied to a copper feedstock will either raise or lower the respective antipathogenic performance and efficacy. Since different copper coating systems achieve various rates of disinfection, as discussed earlier in the present manuscript, the deposition technology known as copper cold spray can be optimized to achieve the maximal inactivation rate in the fight against and management of COVID-19.

Once again, prior work has showcased the noteworthy antipathogenic properties of copper cold sprayed surfaces against Influenza A, MRSA, *Staphylococcus aureus and Pseudomonas aeruginosa*. Given the successful inactivation of more than 97% of the Influenza A virus after two hours of exposure to said conventional copper cold spray surfaces, it stands to reason that the enhanced understanding of the material properties underpinning the antipathogenic performance of copper cold spray material consolidations described herein can be built upon for quick optimization and deployment in hospital and medical environments as a targeted mitigation strategy in response the current COVID-19 pandemic. In fact, the materials science community has also started to advocate for the antipathogenic functionalization of common touch surfaces in public areas through the use of copper in the fight against COVID-19 too [39]. Regarding cold spray, VRC Metal Systems, a manufacturer of cold spray equipment and systems, has also recognized the potential for copper cold spray as preventative technology in response to COVID-19, as highlighted by a blog post released on 27 March2020.

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