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Article

Does Extreme Wettability Matter: The Effect of Copper Wettability on Infection Spread through Hospital Surfaces

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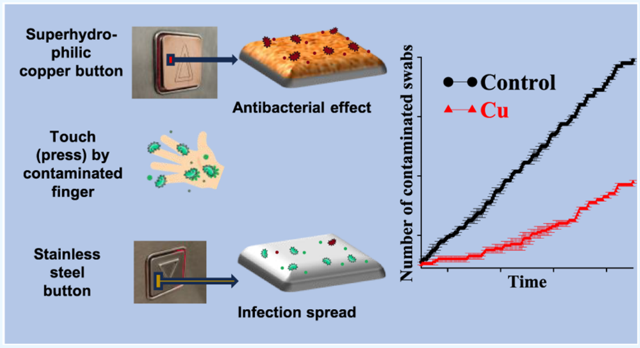
ABSTRACT: One of the reasons for the widespread occurrence of hospital-acquired infections is the ability of microorganisms to survive for extended periods on the indoor surfaces of healthcare facilities. Although the antibacterial properties of copper are well-known and have already been used in medical practice, there is still a lack of research on how extreme wettability of copper-based materials by biological fluids can affect the reduction of surface contamination and, consequently, the spread of hospital-acquired infections, particularly in healthcare settings. This study aims to compare the efficacy of superhydrophilic and superhydrophobic copper surfaces on high-touch facilities such as elevator buttons with smooth copper and stainless steel surfaces in preventing the transfer of infections through hospital surfaces. It was found that the wettability of frequently touched surfaces like elevator buttons matters for combating bacterial contamination. The total aerobic microbial counts, encompassing both pathogenic and nonpathogenic microbial contamination, were similar across smooth, superhydrophobic, and superhydrophilic copper coatings. At the same time, surfaces with extreme wettability exhibited a lower incidence of *Staphylococcus aureus* growth, no growth of *Acinetobacter spp*., and reduced maximum contamination levels for both pathogens and nonpathogenic bacteria. Superhydrophilic buttons treated with the quaternary ammonium compound miramistin showed a reduction in microbial growth during the initial 20 days. The study emphasizes the importance of surface wettability and texture in mitigating microbial contamination.



1. INTRODUCTION

The social costs associated with hospital expenses and the loss of productivity caused by worker distractions from infections result in significant economic losses across various countries.[1,2] Consequently, there is a growing interest in new technologies aimed not only at reducing health risks and loss of life during pandemics but also at preventing and controlling infections. Approaches actively used to suppress the accumulation of viral and bacterial contaminants and their subsequent propagation on surfaces include active sanitation of touch surfaces with antiseptic agents, UV light and ozone treatment, cold plasma treatment, and the deposition of bactericidal substances on touch surfaces, such as quaternary ammonium compounds, antimicrobial peptides, etc.[1,3−6] However, these approaches have a number of limitations that reduce their effectiveness. For example, UV light/ozone treatment can only be performed in the absence of patients and personnel, and limitations of antimicrobial peptides are related to the lack of selectivity and insufficient stability and, in some cases, to high toxicity and potential immunogenicity.[7]

The application of metal self-disinfecting surfaces is currently considered one of the most promising passive technologies as it does not require active involvement from healthcare personnel.[1,8] Among the metal materials with antimicrobial properties, silver, copper, zinc, and titanium, along with their oxides, are noteworthy. Against planktonic bacteria, the metal ions prove to be the most effective, while against sessile bacteria, the hierarchical roughness of the metal provides a stronger effect due to a variety of antimicrobial mechanisms.[8] Among other metals, copper is regarded as one of the most attractive materials for preventing hospital-acquired infections, particularly in healthcare settings.[9−18] At the same time, the passive application of copper surfaces has

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some limitations in use, such as dry environments or organic soiling.[19−22]

However, the impact of surface texturing of copper-based materials, specifically the role of extreme wetting regimes by biological liquids in the reduction of surface contamination and hence the spread of hospital-acquired infections, remained unexplored.

Recent studies[23−28] have shown the high antibacterial potential of superhydrophobic and superhydrophilic copper surfaces in laboratory experiments with a set of well-defined conditions. However, under the conditions of a medical facility, the number of factors that can significantly affect the behavior of copper-based materials during prolonged use increases significantly.

This study aimed to compare the antimicrobial activity of copper-based surfaces with various wettabilities during their exploitation in healthcare settings. The bacterial contamination was monitored for the elevator buttons, which can be considered to be one of the most frequently touched surfaces. The antimicrobial activity of surfaces with wettability ranging from superhydrophilic (characterized by the imbibition of an aqueous medium) to hydrophilic and superhydrophobic (with high water repellency) was analyzed and compared in real hospital conditions.

2. EXPERIMENTAL SECTION

2.1. Objectives and General Design of Study. As previously demonstrated in laboratory experiments, copper-based surfaces with extreme wettability possess significant antibacterial activity.[8,29] This study investigates the antibacterial activity of elevator buttons in real hospital conditions at the Moscow City Clinical Hospital. It is worth noting that the elevator buttons belong to the high-touch surfaces, which makes them very illustrative to demonstrate the antibacterial activity in a real medical unit with hard patient and medical staff traffic. We compared bacterial contamination by various microorganisms on smooth stainless steel buttons, smooth copper buttons, and superhydrophobic and superhydrophilic copper buttons under similar conditions over two consecutive experimental runs with hospital exposure durations of 6 and 4 months.

Considering that laser-textured substrates can be easily loaded with an additional antimicrobial substance through capillary impregnation, one of the superhydrophilic buttons was impregnated with the quaternary ammonium compound, miramistin,[30−32] during the second experimental run. It was anticipated that the release of miramistin from the porous copper button upon pressing would provide an added antimicrobial effect.

The appearance of the elevator buttons installed in various locations is illustrated in Figure S1 in the Supporting Information. Each elevator button had a contact surface area of 8 cm^2. Two buttons of each type were installed in elevator halls positioned in areas with similar patient and medical staff traffic. Video monitoring indicated that each button was touched by approximately 150 ± 55 individuals daily. According to the hospital's standard sanitary protocol, the elevator buttons were disinfected once daily using Avansept Active, a disinfectant based on alkylamine and polyhexamethylene biguanide. To evaluate the microbial contamination of the elevator buttons, swabs were collected from each button four times a week. After each swab was taken from the superhydrophilic button treated with miramistin, an additional liquid was sprayed to replenish the miramistin in the pores.

2.2. Materials. To evaluate the antimicrobial activity of elevator buttons, we cut 1 mm thick flat overlays from sheets of either AISI 304 stainless steel (Prodiel, Russia) or M1M copper alloy (soft copper, ~99.9% Cu, Prodiel, Russia). These overlays were affixed to commercial elevator buttons by using 3 M double-sided tape. Prior to adhesion, one of the three types of copper buttons underwent a preliminary laser treatment to achieve a superhydrophilic state. Another type was laser-treated and subsequently hydrophobized to obtain a superhydrophobic state. The specific parameters for laser processing and the hydrophobization procedure are detailed in our recent publication.[33]

To assess bacterial contamination on test surfaces, sterile cotton buds (LLC MiniMed, Russia) were used to collect the swabs. Nutrient media for cultivating contaminating microorganisms were obtained from the State Research Center for Applied Biotechnology and Microbiology in Obolensk, Russia, including meat-pepton broth, Endo agar, Sabouraud agar, nutrient medium No. 1, and mannitol-salt agar with egg yolk emulsion. Additionally, defibrinated cattle blood serum was sourced from LLC Leitran in Moscow, Russia. Type I deionized water produced by the Arium PRO VF water purification system (Sartorius, Germany) was used to hydrate the cotton swabs, while sterile 0.9 wt % NaCl physiological saline (PanEco, Moscow, Russia) served as the transport medium for delivering the collected swabs to the microbiological laboratory for further processing.

2.3. Characterization of the Test Surfaces. To investigate the evolution of surface morphology and roughness resulting from contact between elevator buttons and the fingers of patients and staff, we employed a confocal microscope (S neox, Sensofar Metrology, Spain), which is equipped with SensoSCAN 2.0 software (Sensofar Metrology, Spain). The primary objective of this study was to identify the influence of the copper surface wettability on antibacterial activity. Therefore, we measured the wettability parameters of the tested surfaces both before and after conducting experiments in a healthcare setting.

The wettability of the test surfaces was characterized by measuring the contact and roll-off/sliding angles of water droplets using custom-made experimental setups, as detailed in previous studies.[34,35] In brief, digital image processing was employed to analyze a 25 μL sessile droplet,[34] allowing us to determine the coordinates of the droplet edge in a cross-section defined by a plane passing through the vertical axis of symmetry of the droplet. A numerical optimization procedure was then applied to find the parameters of the Laplace curve that best fit the determined edge coordinates. These parameters were used to compute the theoretical profile of the droplet and determine the contact angle, surface tension, and other droplet characteristics.

For measuring roll-off or sliding angles (depending on how the droplet moved upon surface inclination[36]), a 15 μL droplet was placed on a horizontally aligned test surface. The surface was then smoothly inclined until the droplet began to move. The results for at least 10 droplets placed at different positions on the test surface were averaged to report each value of contact and roll-off/sliding angles.

2.4. Swab Sampling. Sterile swabs moistened with Type I water were used to collect samples from the test surfaces. Water (2 mL) was applied just prior to collection. For the

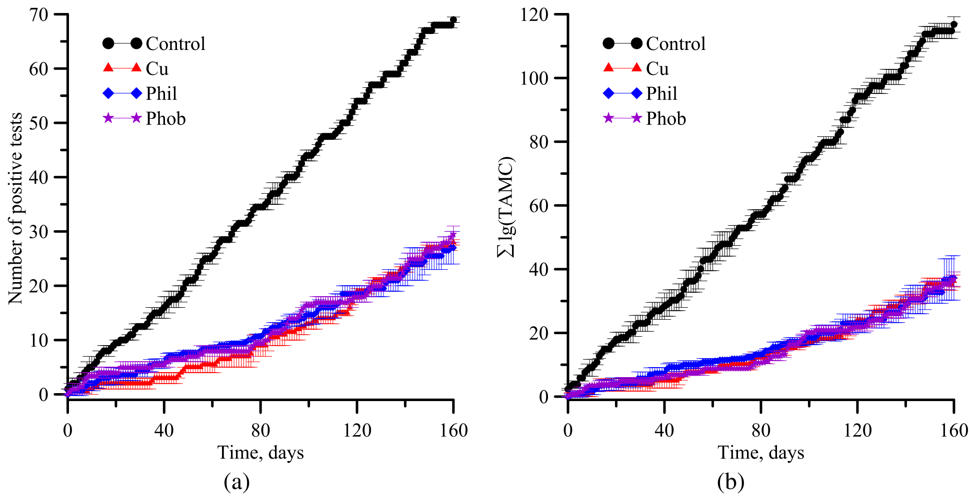

Figure 1. Variation over exposure time in a cumulative number of contaminated swabs taken from elevator buttons with various wettabilities determined by binary count (a) and logarithmic count (b). "Control" in legend stands for stainless steel buttons; "Cu" for untreated copper buttons; "Phil" for laser-treated superhydrophilic copper buttons; "Phob" for laser-treated superhydrophobic copper buttons. TAMC denotes the total aerobic microbial count.

elevator buttons, the swab covered the entire button surface, approximately 8 cm^2. The swabs were taken at 2:00 PM, whereas surface treatment with disinfectants as part of the established daily disinfection routine was performed at 8:00 AM. Each swab containing the collected sample was placed into a tube with transport media (2 mL) and delivered to the microbiological laboratory within 2 h for further processing.

2.5. Swab Processing, Quantification of Contaminations, and Contaminants Identification. To isolate and identify the contaminating microorganisms, several aliquots of the collected probe liquid from the transport tube, each with a volume of 0.1 mL, were inoculated into various nutrient media. Specifically, one aliquot was added to 2 mL of meat-peptone broth, which served as an accumulation medium. Other aliquots were spread onto Petri dishes containing dense nutrient media designed to promote the growth of specific microorganisms. Endo agar was utilized for the isolation of Enterobacterales bacteria, while blood agar served as a general-purpose growth medium to estimate the total aerobic microbial count (TAMC).

Sabouraud agar was used to isolate fungi, while mannitol-salt agar supplemented with egg yolk was employed for the growth of *S. aureus*. The inoculated Petri dishes were incubated under conditions tailored to each specific culture medium: Sabouraud agar at 30 °C for 48−72 h; mannitol-salt agar at 37 °C for 48 h; and both Endo agar and blood agar at 37 °C for 24 h. After the designated incubation period, colonies were counted and pure cultures were obtained from the surface of the nutrient media for subsequent identification. Additionally, the test tube containing the probe added to the accumulation medium was incubated at 37 °C for 24 h. If the accumulation medium became opaque after incubation, a 0.1 mL aliquot was then seeded onto blood agar, serving as a universal nutrient medium, and Sabouraud agar, which is specifically designed for fungal growth. After the appropriate incubation period (consistent with the conditions described for the initial probe samples), the cultivated colonies were collected for mass-spectrometric identification. The TAMC for the collected probe was calculated as the sum of the colonies grown from all aliquots on the different nutrient media and then recalculated this total to express it as colony-forming units per milliliter of the probe (CFU/mL).

To analyze and compare the contamination of all of the buttons, we employed two approaches. The first approach involved a binary assessment of the presence or absence of any type of microorganism on the test surface. If at least one type of microorganism was detected in the swab taken on a specific day, either on a solid nutrient medium or in an accumulation medium, then the result for bacterial contamination on that day was assigned a value of 1. Conversely, if no microorganisms were detected in the analyzed swab, then the result was assigned a value of 0.

However, this binary count approach has a limitation: while it indicates whether microbial contamination is present, it does not reflect the level of contamination. To address this issue, we applied a logarithmic count method. In this approach, when microorganisms were detected in the swab analysis, the outcome was recorded as the decimal logarithm of the TAMC rather than simply as 1. It is important to note that the minimal detectable value of TAMC, as defined previously, is 10; therefore, the logarithmic count will always be equal to or greater than the binary count.

The identification of the collected microorganisms was conducted using MALDI-TOF MS (Matrix-Assisted Laser Desorption/Ionization Time-of-Flight Mass Spectrometry). For this purpose, we utilized the commercially available Bruker Ultraflex Xtreme Biotyper mass spectrometer (Bruker Daltonics, Germany), which is equipped with flexControl 3.4 software. The interpretation of the recorded spectra involved comparing them against the MBT Compass 4.1.100 Reference Library (Bruker Daltonics, Germany).

2.6. Statistical Analysis. The data obtained on the contamination levels of different test surfaces were statistically analyzed using StatSoft STATISTICA 10 software (StatSoft, Russia). To determine the presence of statistically significant differences between the test and control groups of samples, we applied the Mann−Whitney U-test and the Pearson chi-square criterion, with a significance level set at $p \leq 0.05$.

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3. RESULTS AND DISCUSSION

3.1. Study of Antimicrobial Properties. As mentioned earlier, copper is increasingly recognized as a promising material for high-touch surfaces in medical equipment and furniture, aiming at preventing hospital-acquired infections.[8−18] However, the use of copper-based materials with various wettabilities for elevator buttons has not previously been addressed in the literature. Given that elevator buttons are among the most frequently touched surfaces in medical settings, this study focused on analyzing the dynamics of contamination on various types of elevator buttons: stainless steel, smooth copper, superhydrophobic copper, superhydrophilic copper, and superhydrophilic copper impregnated with the quaternary ammonium compound, miramistin. It is important to note that stainless steel is the most commonly used commercial material for elevator buttons.

For each type of elevator button, the cumulative total number of swabs that tested positive for microorganisms was averaged across all buttons of the same type and plotted against the total time of button exposure in the hospital, as shown in Figure 1a. The error bars for each data point in the graph represent the variability in the number of contamination events observed on different buttons with the same wettability.

The antimicrobial activity of modified elevator buttons with various wettabilities was evaluated by comparing the rates of change in the accumulated number of cases where any microorganisms were detected (binary counts) and the accumulated logarithm of the TAMC (logarithmic counts) between test surfaces and standard stainless steel buttons. The two approaches for data analysis presented in Figure 1 show a high degree of similarity in the behavior of cumulative totals, regardless of whether the level of bacterial contamination on the swabs was considered. This similarity is observed across the copper buttons with various wettabilities compared to the standard stainless steel button.

Throughout the clinical trial, the data for smooth, superhydrophilic, and superhydrophobic copper buttons remained close to each other within the confidence interval. Over the 160-day experiment, the difference in bacterial contamination between stainless steel and copper buttons was significant. Specifically, at the end of the trial, the cumulative number of contaminated microorganism swabs from the stainless steel button was 3.3 times higher than that from the copper buttons. Additionally, a comparison of the antibacterial activity between the superhydrophilic button and that impregnated with miramistin revealed a notable reduction in microbial contamination on the miramistin-treated surface for the first 20 days. However, as the trial progressed, the total microbial contamination on the miramistin-filled button was found to be slightly higher than that of the other buttons (Figure 2).

During two sequential clinical trials, the total number of swabs taken was as follows: 228 swabs from each steel, copper, and superhydrophilic copper button, 168 swabs from superhydrophobic buttons, and 57 swabs from a superhydrophilic button impregnated with miramistin.

The fraction of swabs that showed the growth of various microorganisms for each type of elevator button is shown in Figure 3. The data indicate that copper buttons, regardless of their wettability, exhibit comparable levels of bacterial contamination, with a contamination rate that is 65% lower than that of control stainless steel buttons (with a significance level of $p < 0.05$).

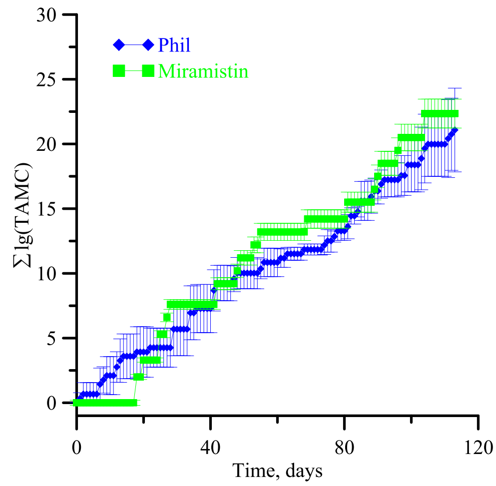

Figure 2. Variation over exposure time in the cumulative logarithm of the total aerobic microbial count (TAMC) from contaminated swabs collected from superhydrophilic copper elevator buttons. "Phil" in legend stands for laser-treated superhydrophilic copper buttons, while "Miramistin" for those that were replenished with miramistin after each swab was taken.

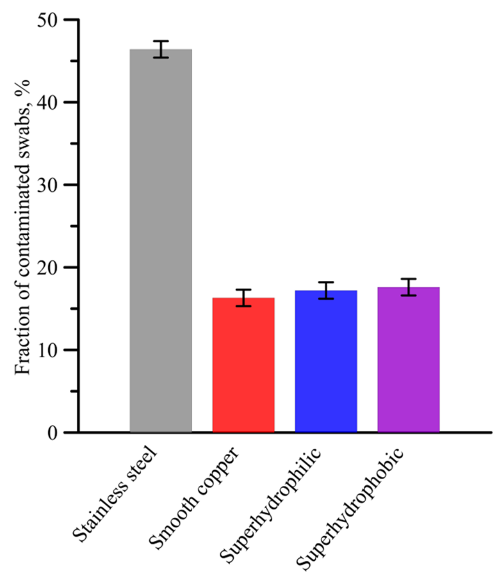

Figure 3. Fraction of contaminated swabs collected from elevator buttons.

The data on the number of swabs showing bacterial growth and the maximum contamination levels of test samples for various healthcare-associated infection (HAI) pathogens as well as representatives of the human and environmental microbiome are presented in Figure 4. It is worth noting that in multiple swabs from the test buttons several types of microorganisms were simultaneously found. Additionally, not all representatives of the human and environmental microbiome identified during the clinical trial are included in the table. Due to the low incidence of growth for some microorganisms and the resulting low statistical reliability of their detection, information on these specific microorganisms is not provided.

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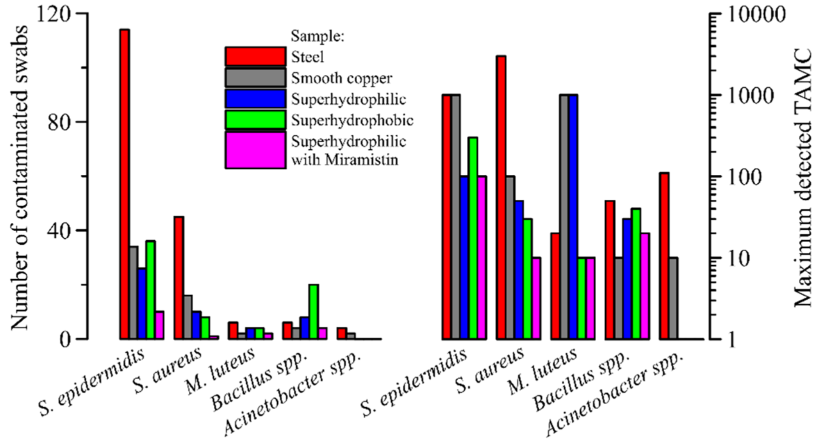

Figure 4. Species and genus of microorganisms most frequently isolated from tested elevator buttons: (a) number of swabs where a particular strain was detected; (b) maximal contamination levels detected for the strain.

The analysis of data in Figure 4 reveals significant differences in contamination levels of various buttons by *Staphylococcus aureus* (*S. aureus*) over the observation period. The maximum detected contamination levels were 3000 CFU/mL for stainless steel, 100 CFU/mL for smooth copper, 50 CFU/mL for superhydrophilic copper, and 30 CFU/mL for superhydrophobic copper. With a significance level of $p < 0.05$, the smooth copper button exhibited a contamination level that was 30 times lower than that of the stainless steel button, while the superhydrophobic coating showed a 100-fold reduction in contamination. Additionally, the incidence of *S. aureus* growth was approximately five times lower on superhydrophilic and superhydrophobic copper buttons compared to that on the stainless steel button.

A similar trend was observed with *Acinetobacter spp*., where the smooth copper button demonstrated an 11-fold reduction in maximum contamination compared with the stainless steel button. Notably, no growth of *Acinetobacter spp*. was detected in swabs from the superhydrophilic and superhydrophobic substrates throughout the observation period. Conversely, *Micrococcus luteus*, a component of mammalian skin microbiota, showed a tendency to settle on both smooth copper and superhydrophilic copper buttons. Regarding the antibacterial activity of the superhydrophilic copper button impregnated with the antimicrobial agent miramistin, the data presented in Figures 2 and 4 did not indicate a significant enhancement in antimicrobial effect compared to the nonimpregnated superhydrophilic button. This suggests that the anticipated synergistic effect of superhydrophilicity and the antiseptic properties of the quaternary ammonium compound were not observed.

An important aspect that warrants discussion in relation to the antimicrobial activity mentioned above is the evolution of initial wettability and the morphology of high-touch surfaces during prolonged exposure in healthcare settings. This topic is explored in the following sections.

3.2. Evolution of the Test Surface Wettability and Roughness during the Clinical Trials. To better understand the differences in contamination levels observed for smooth steel, smooth copper, and superhydrophilic and superhydrophobic surfaces, we studied the evolution of wettability for all types of test samples. The contact angles measured for the elevator buttons, both freshly prepared and after prolonged exposure in healthcare settings, are presented in Figure 5.

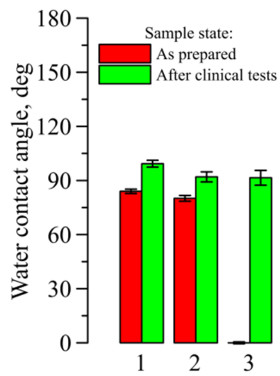

Figure 5. Water contact angles on test surfaces before and after evaluating their antibacterial effects under clinical conditions: (1) stainless steel; (2) smooth copper; (3) superhydrophilic copper; (4) superhydrophobic copper; and (5) superhydrophilic copper impregnated with the miramistin.

The contact angle values for fresh, smooth steel and copper buttons presented in Figure 5 indicate the hydrophilic nature of these metal surfaces. The values measured for steel are consistent with those reported in the literature.[37,38] In contrast, the contact angle values for the copper surface are slightly higher than those recently reported.[39,40] We attribute these increased values to the fact that to simulate conditions typically found in a hospital environment, the samples, after being cleaned in an ultrasonic bath with ethanol and acetone, were stored in the laboratory for 2−3 days prior to wettability measurements. This storage period allows for the spontaneous adsorption of airborne contaminants on the clean surface, resulting in an increase in the contact angle value.[41]

The large scattering in the reported contact angle values for smooth substrates prior to the clinical trial can be attributed to the use of commercial products that were not certified for chemical homogeneity and uniform roughness. The large standard deviation observed in the measured contact angles for elevator buttons following clinical exposure is clearly related to the chemical and spatial nonuniformity resulting from repeated finger contact. The initial water contact angle values for the laser-textured surfaces of buttons were nearly zero, indicating

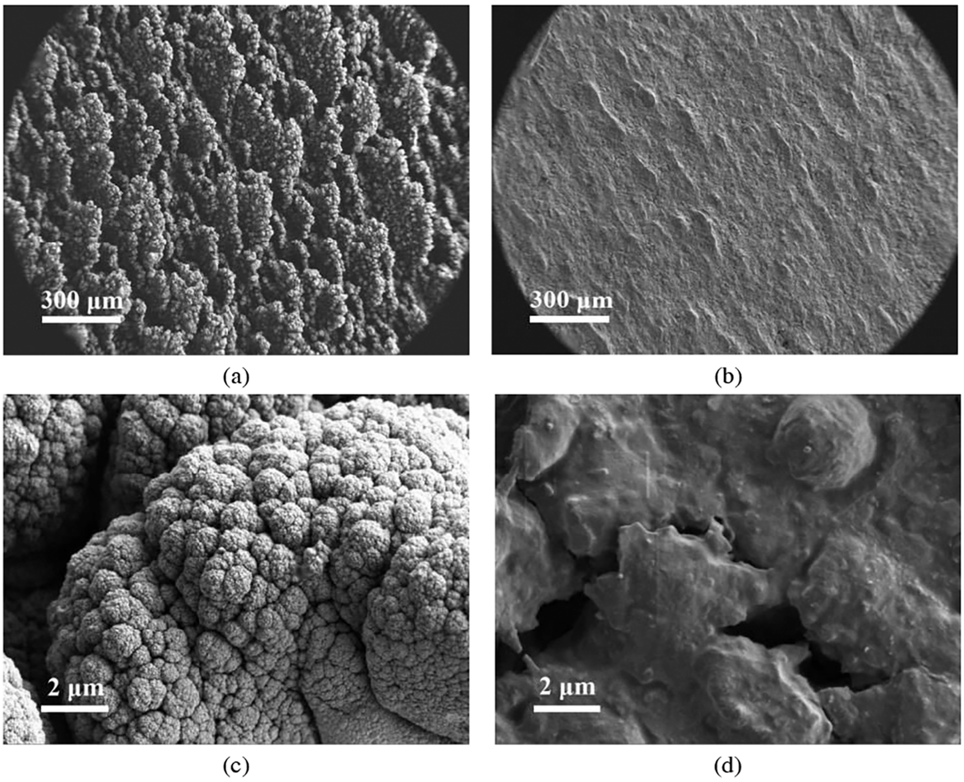

Figure 6. SEM images of the surfaces of superhydrophilic copper elevator buttons before (a, c) and after (b, d) 6 months of clinical tests.

Table 1. Roughness Parameters of Test Samples before and after Clinical Tests

type of samples		S_a[a], μm	S_{ratio}[a]	S_q[a], μm	S_z[a], μm
stainless steel	freshly fabricated	0.174 ± 0.001	1.002 ± 0.000	0.220 ± 0.001	2.2 ± 0.3
	after trial	0.205 ± 0.002	1.007 ± 0.000	0.262 ± 0.002	2.3 ± 0.1
smooth copper	freshly fabricated	0.182 ± 0.000	1.001 ± 0.000	0.254 ± 0.003	4.6 ± 0.7
	after trial	0.43 ± 0.02	1.001 ± 0.000	0.577 ± 0.015	6.7 ± 1.4
superhydrophilic copper	freshly fabricated	33.9 ± 3.1	3.2 ± 0.2	40.2 ± 3.3	240 ± 30
	after trial	2.8 ± 1.2	1.11 ± 0.04	4.1 ± 1.1	77 ± 22
superhydrophobic copper	freshly fabricated	34.9 ± 2.1	3.2 ± 0.2	41 ± 2	243 ± 24
	after trial	2.6 ± 0.4	1.11 ± 0.02	3.6 ± 0.6	58 ± 14

[a]S_a, the arithmetic mean height of the surface; S_{ratio}, the ratio between the actual and projected surface area; S_q, the root-mean-square height of all data points from the mean surface height; S_z, the sum of the largest peak height value and the largest pit depth value.

complete aqueous droplet spreading and confirming the superhydrophilic state of these surfaces after laser texturing.

The comparison of contact angles before and after the clinical trial reveals significant changes in the wettability of superhydrophilic buttons alongside a notable increase in contact angles for smooth steel and copper buttons. The observed changes in the button wettability are attributed to contamination from finger contact. It is important to note that regardless of their initial wettability, copper elevator buttons exhibit weak hydrophobicity after prolonged exposure in a hospital setting, with an average contact angle slightly exceeding 90°. The most straightforward explanation for the observed changes in wettability may be attributed to the abrasion of the hierarchical texture on both the superhydrophobic and superhydrophilic elevator buttons. To confirm this hypothesis, we compared the SEM images of elevator buttons at different magnifications (Figure 6) and conducted an analysis of the roughness of all surfaces before and after the clinical testing. The roughness parameters for the elevator buttons, determined in accordance with ISO 25178, are summarized in Table 1. Additionally, 3D maps of the button surfaces exhibiting various wettabilities are presented in Figure 7.

The analysis of the data presented in Figure 7 and Table 1 indicates that microscopic scratches developed during clinical trials on smooth stainless steel and copper elevator buttons had a minimal impact on the S_{ratio}. It is important to highlight that it is the S_{ratio} that largely determines the contact angle in the homogeneous wetting regime. Additionally, it was observed that the depth of scratches on the softer copper buttons was greater than that on the stainless steel buttons. In contrast, the laser-textured superhydrophobic and superhydrophilic buttons exhibited a significant reduction in S_{ratio} after clinical testing, with values approximately three times lower than those of freshly prepared coatings. Furthermore, the parameters S_a, S_q, and S_z for these textured samples decreased by factors of 5 to 10 after the clinical trials.

The evolution of the surface relief can be attributed to both the intense abrasion of the texture on the touch surfaces by fingers and the filling of the texture with biological materials

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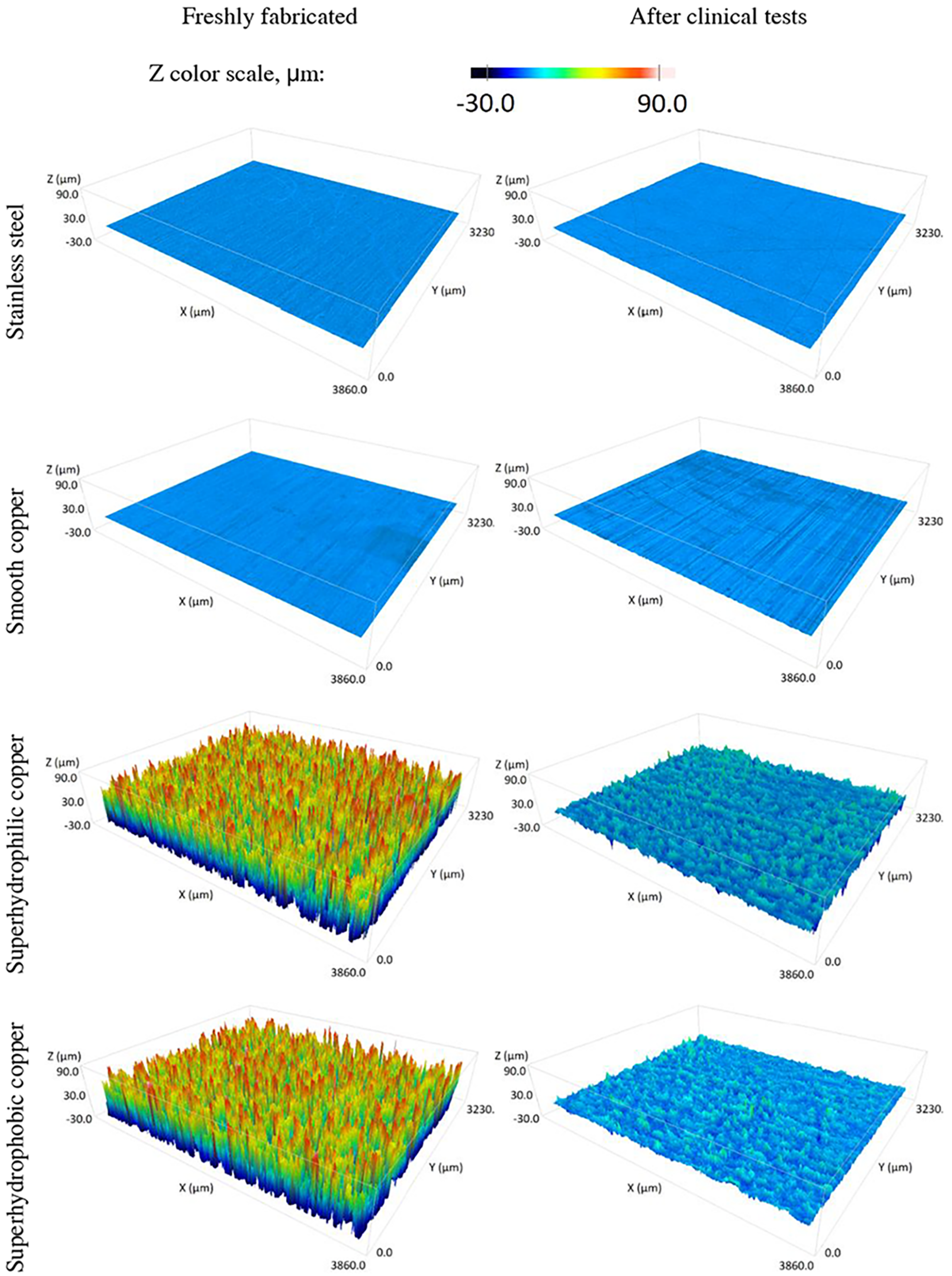

Figure 7. 3D maps of the elevator button surfaces with various wettabilities before and after the clinical tests.

transferred from fingers into grooves during button presses. Notably, after the clinical trials, the S_{ratio} values for smooth, superhydrophobic, and superhydrophilic copper buttons were found to be very similar. This similarity helps explain the

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nearly identical contact angles observed for surfaces subjected to the same level of chemical contamination. Interestingly, the significantly higher contact angle measured for the superhydrophilic copper button treated with miramistin can be attributed to the pronounced hydrophobicity of benzyldimethyl[3-(myristoylamino)propyl]ammonium chloride, the component of miramistin, which features a long hydrophobic tail. As this hydrophobic substance accumulates within the grooves of the textured button during periodic spraying, it alters the surface characteristics, rendering the button effectively hydrophobic.

3.3. Impact of Wettability on the Antimicrobial Properties. Now, let us examine the role of surface wettability in the antibacterial properties of elevator buttons. As previously discussed, the frequency of bacterial contamination events for smooth, superhydrophilic, and superhydrophobic copper elevator buttons was found to be consistent and 65% lower than that of standard stainless steel buttons throughout the entire clinical trial.

At the initial stages of a clinical trial of surfaces with extreme wetting, when the hierarchical roughness is presented in both superhydrophilic and superhydrophobic buttons, as was discussed in the literature, two mechanisms of bacteria killing are relevant. These are the copper ions release and the mechano-bactericidal effect. The first mechanism is active on any copper surface under humid conditions. The second one, associated with the nano- and microfeatures of the textured surfaces, involves the piercing, deformation, and stretching of cell membranes, particularly for cells that exhibit high adhesion to the surface.[8,33,42,43] At prolonged clinical trials, filling the texture with biological materials transferred from fingers into the grooves of the texture occurs rapidly, which is expected given that the average number of button presses per day is approximately 150. Additionally, the mechanical loads associated with pressing the buttons lead to wear of the nanotexture (as illustrated in Figures 6 and 7), resulting in a partial loss of hierarchical roughness, leading to degradation of both superhydrophobic and superhydrophilic states.

After the prolonged trial, the wettability of the stainless steel buttons was comparable to those of all types of copper buttons. From this data and surface morphology (Table 1 and Figure 6), we can conclude that the antibacterial properties of copper buttons upon prolonged use as touch surfaces are mainly associated with the release of copper ions. Nevertheless, despite the above alteration of surface properties, our experiments revealed significantly fewer instances of *S. aureus* growth and lower maximum contamination levels on the initially textured buttons with extreme wettability. This observation suggests that the mechano-bactericidal mechanism of cell killing retains some activity, even as the main part of the surface texture degrades. Notably, *Acinetobacter spp.* was not detected in swabs taken from surfaces initially exhibiting extreme wettability.

4. CONCLUSIONS

The potential of copper coatings with various wettabilities in reducing the microbial burden on hospital touch surfaces, such as furniture and equipment, and consequently lowering rates of healthcare-associated infections is an area of significant interest, though it has not been fully elucidated until now. In this study, we conducted systematic investigations of high-touch elevator buttons to assess the antimicrobial activity of copper surfaces with various wettabilities and compared this activity to that of corresponding steel surfaces. Taking into account that the majority of biological liquids with a wide range of compositions are solutions or dispersions in the aqueous phase, we have characterized the wettability of our surface by the water contact angle. As our previous studies[44,45] have shown, although contact angles formed on the top of hierarchically rough substrates by droplets of, say, water-based bacterial dispersions or bacterial dispersions in an aqueous phase saturated with an organic component, may differ slightly from each other, extreme wettability with respect to water is preserved for biological liquids as well.

Our findings revealed that high-touch copper coatings, regardless of their wettability, exhibited 65% higher antimicrobial activity compared to stainless steel surfaces in terms of the total aerobic microbial count. This suggests that copper coatings could provide a valuable strategy for enhancing infection control in healthcare settings.

Based on the results of in vitro experiments,[8] it was anticipated that copper coatings with extreme wettability would demonstrate higher antimicrobial activity compared to smooth coatings. However, our experiments conducted with elevator buttons in a high-traffic medical unit revealed similar logarithmic counts of total aerobic microbial counts on smooth, superhydrophobic, and superhydrophilic coatings. This phenomenon was interpreted as a consequence of significant variations in wettability due to morphological changes and chemical contamination of the buttons, resulting from repeated contact. Despite this, the low incidence of *S. aureus* growth and the complete absence of *Acinetobacter spp.* growth from swabs taken from coatings initially exhibiting extreme wettability suggest distinct advantages for surfaces with such properties. This is particularly notable in the context of lower maximum contamination levels observed on these buttons. The effectiveness of these extreme wettability surfaces is likely attributed to the mechano-bactericidal mechanism of cell death, which is characteristic of surfaces featuring micro- and nanotextural elements.

The attempts to leverage the combined effects of liquid antiseptics, such as miramistin, alongside the antimicrobial properties of superhydrophilic copper buttons have not proven to be entirely successful. This is primarily due to the limited initial activity period, which lasted approximately 20 days, during which nearly zero microbial contamination was observed on the surfaces treated with miramistin. Nevertheless, considering the simplicity and low cost associated with the replacement of such buttons, it remains an attractive and reasonable strategy to utilize superhydrophilic copper buttons impregnated with miramistin in high-traffic healthcare settings. Implementing periodic replacements could enhance antimicrobial efficacy and contribute to improved infection control in these environments.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.5c01931.

Images of elevator buttons (PDF)

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Notes

The authors declare no competing financial interest.

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