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Healthcare environments in pulmonary rehabilitation units: Effective infection control through integration of long-term antimicrobial materials

Ke-Yun Chao[1,2,3,4], Chao-Yu Chen[5,6], Wei-Lun Liu[7,8], Jyun-Sain Wu[7], Yu-Tzu Huang[7]

[1]Department of Respiratory Therapy, College of Medicine, Fu Jen Catholic University, New Taipei City, Taiwan; [2]Cardiovascular and Pulmonary Rehabilitation Center, Fu Jen Catholic University Hospital, Fu Jen Catholic University, New Taipei City, Taiwan; [3]Telehealth Center, Fu Jen Catholic University Hospital, Fu Jen Catholic University, New Taipei City, Taiwan; [4]Artificial Intelligence Development Center, Fu Jen Catholic University, New Taipei City, Taiwan; [5]Department of Respiratory Therapy, Fu Jen Catholic University Hospital, Fu Jen Catholic University, New Taipei City, Taiwan; [6]Department of Life Science, Fu Jen Catholic University, New Taipei City, Taiwan; [7]School of Medicine, College of Medicine, Fu Jen Catholic University, New Taipei City, Taiwan; [8]Department of Critical Care Medicine, Fu Jen Catholic University Hospital, Fu Jen Catholic University, New Taipei City, Taiwan

ABSTRACT

Background: Chronic obstructive pulmonary disease is a leading cause of morbidity and mortality worldwide. Effective infection control in pulmonary rehabilitation units is essential but remains insufficiently studied. This study investigated bacterial contamination, the distribution of species, and the effectiveness of antimicrobial strategies in a pulmonary rehabilitation center.

Methods: Surface swab sampling and ZnO-based antimicrobial strategies were employed to assess bacterial contamination in a pulmonary rehabilitation center. The swab samples were cultured, and species were identified.

Results: Bacterial contamination on six key sampling surfaces was initially high (over 500 CFUs/100 cm^2) but was significantly reduced after the application of ZnO tape to these surfaces. The antibacterial rates exceeded 80% after one week of using ZnO tape and nanoparticle suspension; however, on some surfaces, the effectiveness declined even after three weeks. These findings suggest that antibacterial protection should be renewed weekly to maintain its efficacy.

Conclusions: The application of ZnO tape and nanoparticle solution effectively reduced bacterial contamination in a pulmonary rehabilitation center, underscoring the need for regular disinfection and innovative infection control strategies.

Key words: Contamination, antimicrobial, zinc oxide, pulmonary rehabilitation unit, infection control

Correspondence: Yu-Tzu Huang, School of Medicine, College of Medicine, Fu Jen Catholic University, New Taipei City, Taiwan; No.510, Zhongzheng Rd., Xinzhuang Dist., New Taipei City 24205, Taiwan; Tel: +886-2-29053499; E-mail: 061337@mail.fju.edu.tw

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Availability of data and material: The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

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Introduction

Chronic obstructive pulmonary disease (COPD) is a leading cause of morbidity and mortality worldwide and imposes heavy economic and social burdens on health-care systems [1-3]. Substantial evidence supports the efficacy of pulmonary rehabilitation as a nonpharmacological approach to treatment for stable COPD. Chronic inflammation is a fundamental pathophysiological mechanism underlying major lung damage and a compromised immune system in COPD [4, 5].

Chronic inflammation not only deteriorates lung function, but also impairs the ability of the patient to effectively resist respiratory infections, resulting in a cycle of recurrent infections that further exacerbate COPD. Numerous studies have demonstrated that immune dysfunction—both lung-specific and systemic—is closely linked with the progression and overall severity of COPD [6-9].

In the hospital setting, pathogens are transmitted through various means, including direct skin-to-skin contact between health-care workers and patients [10, 11] and contact with contaminated environmental surfaces, including medical equipment and electronic devices such as computer keyboards [12-14]. Consequently, effective hand hygiene protocols and rigorous environmental cleaning strategies must be adopted to mitigate the spread of pathogens. Essential hand hygiene practices, including washing hands regularly [15-18] and changing gloves when necessary [16, 19], play a pivotal role in bolstering infection control efforts. However, multiple studies have highlighted concerningly low adherence to hand hygiene practices in hemodialysis units, with this adherence influenced by the ratio of staff to patients. This discrepancy exposes a significant gap between ideal practices and their real-world implementation [20-22].

Zinc Oxide (ZnO) is widely used in various skin treatments, including baby powder, bandages, antibacterial ointments, burn dressings, sunscreens, creams, and lotions [23-27]. It is gentle, non-irritating, non-allergenic, and safe for skin contact [27-29]. The antibacterial mechanism of ZnO involves an interaction between the positive and negative charges of bacterial cell walls, leading to the release of positive ions that disrupt the internal balance of bacterial cells. This disruption interferes with bacterial metabolic functions, inhibiting reproduction and achieving an active antibacterial effect [30, 31]. As an essential element for the growth of many natural organisms, zinc does not disrupt natural cycles or metabolism and is considered relatively environmentally friendly [32].

The environment within a medical facility, if not adequately cleaned and disinfected, can be a potential source of pathogens. Several studies have highlighted the importance of practicing environmental hygiene in hemodialysis units [33-35]. The Centers for Disease Control and Prevention (CDC) have developed specific recommendations and checklists for disinfection of dialysis stations, emphasizing the need for thorough cleaning after a patient has left the hemodialysis unit [36]. However, research is limited on the specific aspects of environmental hygiene in pulmonary rehabilitation units. Therefore, this study investigated the incidence of bacterial contamination, the distribution of species on devices and within the environment, and the effectiveness of established antimicrobial strategies in a pulmonary rehabilitation unit providing care for ambulatory patients.

Methods

Study design

This single-center, open-label, prospective study was conducted in a pulmonary rehabilitation center at Fu Jen Catholic University Hospital, New Taipei City, Taiwan, from December 2022 to May 2023. The study was approved by the Institutional Review Board of Fu Jen Catholic University Hospital (FJUH112259). This study was executed and reported in accordance with Standards for QI Reporting Excellence (SQUIRE) 2.0 [37].

Study location and routines

The pulmonary rehabilitation center that was the site of this study is equipped with four negative pressure ventilators, three high-frequency chest wall oscillation devices, and four exercise training machines. The center operates daily from 08:30 to 21:00 and is

cleaned and disinfected daily using 75% alcohol at three time points: before it opens for the day, during the midday break, and after it closes. Respiratory therapists sanitize their hands with 75% alcohol before and after each patient interaction as part of routine recurrent cleaning to prevent cross-contamination. Additionally, the seating area is disinfected using an alcohol spray after each treatment session. This pulmonary rehabilitation center specifically serves ambulatory patients and averaged 1,250 outpatient visits per month between August and November 2022. The majority of patients are diagnosed with chronic respiratory conditions, including bronchiectasis, COPD, asthma, and pulmonary fibrosis. Patients were routinely administered nebulized, short-acting beta-agonists through single-use jet nebulizers provided by the center prior to an exercise session to mitigate the risk of exercise-induced bronchoconstriction [38].

Study protocol

To analyze the distribution of bacteria in the pulmonary rehabilitation center, the devices and environment within the center were coded into 16 items (Fig. 1A). The contact points on various surfaces were swabbed. Environmental samples were collected from the wall, floor, and mice connected to a PC. All the relevant surfaces were swabbed 4 weeks before implementation of the antimicrobial strategy and 1 and 3 weeks after its implementation.

Antimicrobial strategy

The antimicrobial strategy primarily involved the use of long-lasting ZnO antibacterial tape (Durable Zinc Oxide Antimicrobial Tape, STC Nanotech Applied Science, Taiwan) [39] and ZnO antibacterial spray (Nanotech Zinc Oxide Long-Lasting Antibacterial Spray, STC Nanotech Applied Science, Taiwan) [40]. Tape pieces measuring 5 × 5 cm^2 or 10 × 10 cm^2 were applied to the panels and touchscreens of the high-frequency chest wall oscillation devices (named AW-1 to AW-3), negative pressure ventilators (NP-1 to NP-4), and ergometers (EX-3 and EX-4) as well as to surrounding surfaces, such as the PC mice (MS-1 and MS-2), wall locations (WA-1 and WA-2), and floor (FL). Owing to a limited amount of material, the ZnO tape was only applied to the handles of the treadmill (EX-2). Moreover, the foam grip of the recumbent bike (EX-1) was unsuitable for taping; therefore, ZnO nanoparticle suspension (STC Optics, Taiwan) was used to disinfect the handles of the recumbent bike instead (Fig. 1A). During the antimicrobial phase, routine cleaning and disinfection with 75% alcohol was discontinued for the ZnO-protected surfaces.

Bacterial sampling, culture, and analysis

Following implementation of the antimicrobial strategy, an area of 5 × 5 cm^2 or 10 × 10 cm^2 was swabbed at each sampling site. The moisture from the cotton swab was squeezed into a microcentrifuge tube containing 0.5 mL of lysogeny broth. The bacterial suspension so obtained was extended on glass beads placed on plates of blood agar and lysogeny broth agar. The plates were gently swirled and rolled on a glass tabletop to evenly disperse the bacterial inoculum, after which the glass beads were removed, and the plates were incubated at 37°C for 48 hours. Bacterial growth was monitored during this period by determining the number of colony-forming units (CFUs). All samples were cultured in the Bacteriology Laboratory of Fu Jen Catholic University and identified in the Bacteriology Laboratory of Fu Jen Catholic University Hospital. Microbial identification was performed using the automated VITEK 2XL system (bioMérieux, Marcy l'Etoile, France), which utilizes growth-based technology.

Statistical analysis

The number of colonies in each group of samples is expressed as the number of CFUs/100 cm^2. The antibacterial rate, expressed as a percentage, was calculated as the bacterial number at baseline divided by the bacterial number at 1 week or 3 weeks after implementation of the antimicrobial strategy.

Results

The results indicated that the total bacterial density exceeded 500 CFUs/100 cm^2 for six sampling

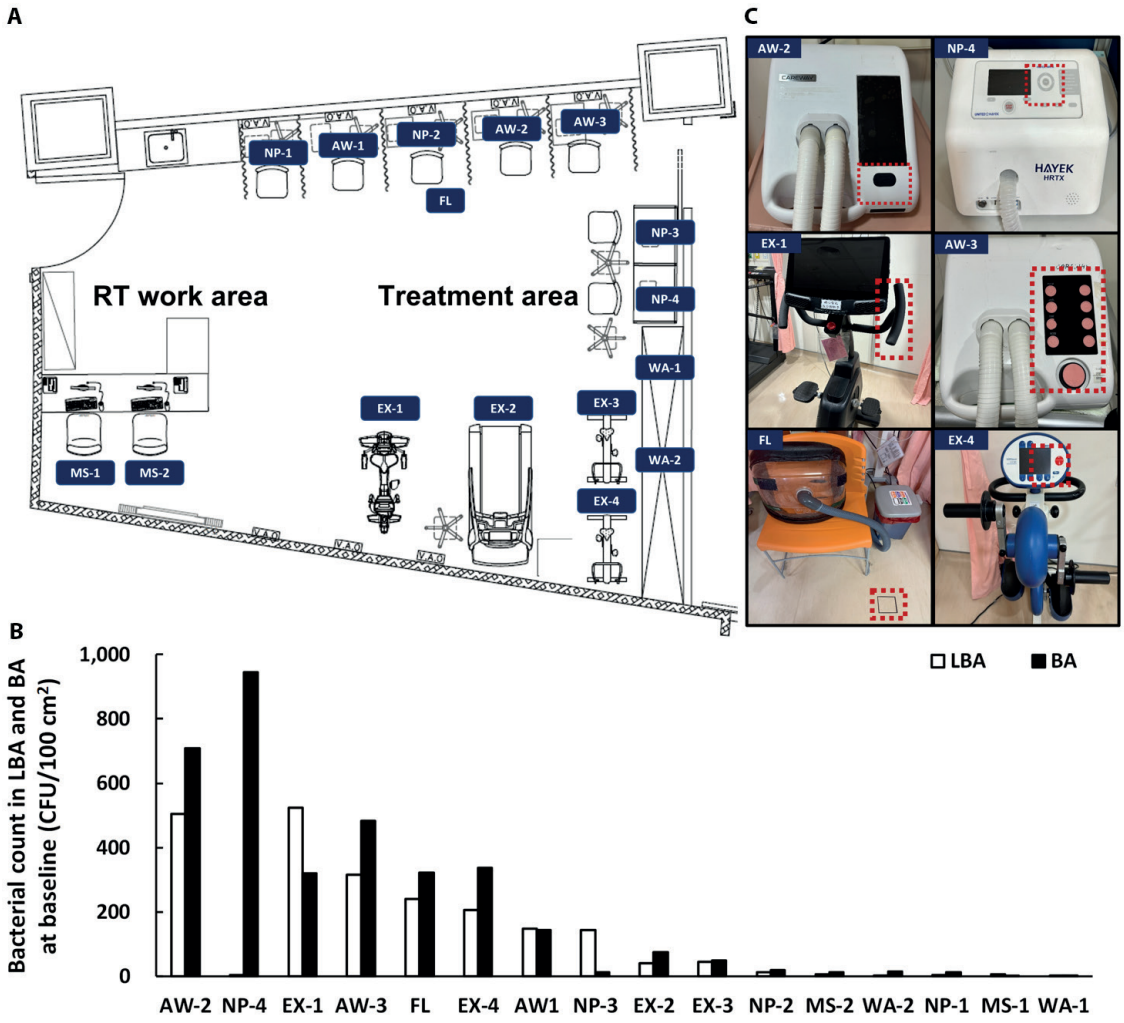

Figure 1. Baseline screening of bacterial concentrations on various equipment and environmental surfaces in the pulmonary rehabilitation center. (A) Floor plan of the pulmonary rehabilitation center and location of the 16 coded areas. (B) Bacterial counts at the 16 coded areas. (C) Six equipment surfaces with the highest bacterial contamination. RT: respiratory therapist; AW: high-frequency chest wall oscillation device; NP: negative-pressure ventilator; EX: exercise training equipment; FL: floor; MS: mouse; WA: wall; LBA: lysogeny broth agar; BA: blood agar.

points: AW-2, NP-4, EX-1, AW-3, FL, and EX-4. The bacterial density for the other 10 sampling points was relatively low (Fig. 1B). The aforementioned six sampling points were flagged as areas of contamination concern that require active infection control efforts (Fig. 1C). Bacteria were primarily distributed in the treatment area, whereas their density was lower in the work area of the respiratory therapists and on the wall. The contact surfaces between operators and devices, such as the touching panels (AW-2, NP-4, AW-3, and EX-4) and the foam grip of the recumbent bike (EX-1), are naturally likely to accumulate the most bacteria. Additionally, bacteria are expected to accumulate on the floor (FL) due to coughing and dispersion of aerosol particles during nebulization.

The species and quantities of bacteria at the four most contaminated sampling points were further analyzed to identify the types of bacteria present and their biosafety risk groupings, as outlined in the *Laboratory Biosafety Manual* by the World Health Organization (Fig. 1C) [41, 42]. In addition to some risk group 1 bacteria, several species of risk group 2 bacteria were

detected (Table 1), highlighting a risk of nosocomial infection in the treatment area. *Staphylococcus haemolyticus* was the most common bacterial contaminant identified in this investigation. Additionally, *Kocuria kristinae* (renamed *Rothia kristinae* in 2018) was abundant on AW-3, which warrants further investigation. Furthermore, as demonstrated by the data in Table 1, using two culture media for bacterial cultivation enabled the identification of more pathogenic bacteria because it supported the growth of cultures with varying nutritional requirements.

Figure 2 shows snapshots of bacterial cultures on lysogeny broth agar and blood agar, derived from the four most contaminated sampling points at the three time points (baseline, 1 week, and 3 weeks). The data indicated a notably reduction in bacterial counts at the end of the first week following implementation of the antimicrobial strategy, highlighting the effectiveness and long-lasting effects of the strategy. Even at the end of 3 weeks, some antibacterial effects were evident and colony growth was minimal, suggesting the presence of slowly replicating bacterial strains.

The findings indicated a decrease in bacterial numbers at the 1-week time point irrespective of whether the bacteria were cultured on lysogeny broth agar or blood agar (Fig. 3A). The antibacterial rates for most sampling surfaces exceeded 80% at the 1-week time point, with the rates for some surfaces even approaching 100% (Fig. 3B). However, the bacterial counts notably differed among the various sampling surfaces at the 3-week time point. Although the antibacterial rate remained high for some surfaces (AW-2, EX-1, and EX-4), the bacterial count increased for other surfaces (NP-4, AW-3, and FL). These findings suggest that antibacterial protection measures should ideally be renewed on a weekly basis to maintain their efficacy.

Discussion

This study analyzed the distribution of bacteria within the pulmonary rehabilitation center of Fu Jen Catholic University Hospital to help establish effective infection control measures. The results revealed that 6 sampling points had high bacterial counts, whereas the remaining 10 points—equivalent to two-thirds of the total sampling area—exhibited relatively low bacterial counts. In the sampling points AW-2, AW-3, and NP-4, positioned at the corner of the treatment area, crossover contamination was suggested to have occurred due to exhaled air and dispersed particles. Additionally, FL was identified as a key site for bacterial accumulation, likely resulting from coughing and particle dispersion during nebulization. The foam grip of the recumbent bike (EX-1), being a porous surface, was expected to be less resistant to contamination compared with nonporous surfaces [43].

Studies have reported high contamination rates for computer keyboards and mice [44-46]. Surprisingly, the mouse used by respiratory therapists in this study was found to not be contaminated, which suggests the maintenance of good hand hygiene practices among the staff. In general, commonly used surfaces should be periodically screened for contamination so that the distribution of bacteria on these surfaces can be discerned and infection control strategies can be devised in advance.

Hospitals commonly use disinfectants or 75% alcohol to eliminate microorganisms quickly, but these chemicals can only inactivate the microorganisms or temporarily suppress their growth [47]. Therefore, we utilized a long-lasting antibacterial nanometal to protect contact surfaces from contamination. Physical methods such as ZnO-coated tape facilitate thorough contact between nanoparticles and the surface of medical equipment and thereby have favorable antibacterial effects. Additionally, antibacterial agents derived from nanometals retain their antibacterial properties under high-temperature and high-pressure conditions [47].

Most antibacterial methods achieve quick sterilization and disinfection through chemical agents, such as alcohol and sodium hypochlorite solution. However, these chemical agents can cause varying degrees of irritation to the human body; sensitive areas such as the skin, eyes, mouth, and nose may experience a itching or stinging sensation, and extra caution must thus be exercised when using these chemical agents [48]. By contrast, physical antibacterial methods utilize positive and negative ions to destroy bacterial cell walls, increasing the levels of reactive oxygen species within the bacteria, resulting in contact sterilization [49, 50]. Common physical antibacterial methods include the

Table 1. Analysis of bacterial species and CFUs per 100 cm² on equipment surfaces.

		AW-2		NP-4		EX-1		AW-3	
Classification	**Bacterial species**	**LBA**	**BA**	**LBA**	**BA**	**LBA**	**BA**	**LBA**	**BA**
Risk group 1	*Dermacoccus nishinomiyaen*						30		
	Kocuria rosea			7	15				
	Micrococcus luteus					30	65		
Risk group 2	*Acinetobacter lwofii*	15				1			
	Acinetobacter schindleri			6					
	Kocuria kristinae (Rothia kristinae)		50			55		20	>1000
	Roseomonas gilardii					10			
	Staphylococcus epidermidis		8			20			
	Staphylococcus haemolyticus	1	35	10	30	25	20	60	15
	Staphylococcus hominis		4	10					
	Staphylococcus pettenkoferi				10				
	Staphylococcus saprophyticus						15		
	Staphylococcus vitulinus						16		
	Staphylococcus warneri	10		1	10			10	12
Unable to classify	*Bacillus megaterium*							1	
	Bacillus spp.	1	4			3	5	3	1
	Micrococcus lylae			8					
	Unidentified Gram positive *bacillus*		1		8	4	6		2
	Unidentified Gram positive *cocci*								30

CFU: colony forming unit; LBA: lysogeny broth agar; BA: blood agar.
Biosafety risk groupings were classified based on the guidelines provided in the *Laboratory Biosafety Manual* by the World Health Organization [42].

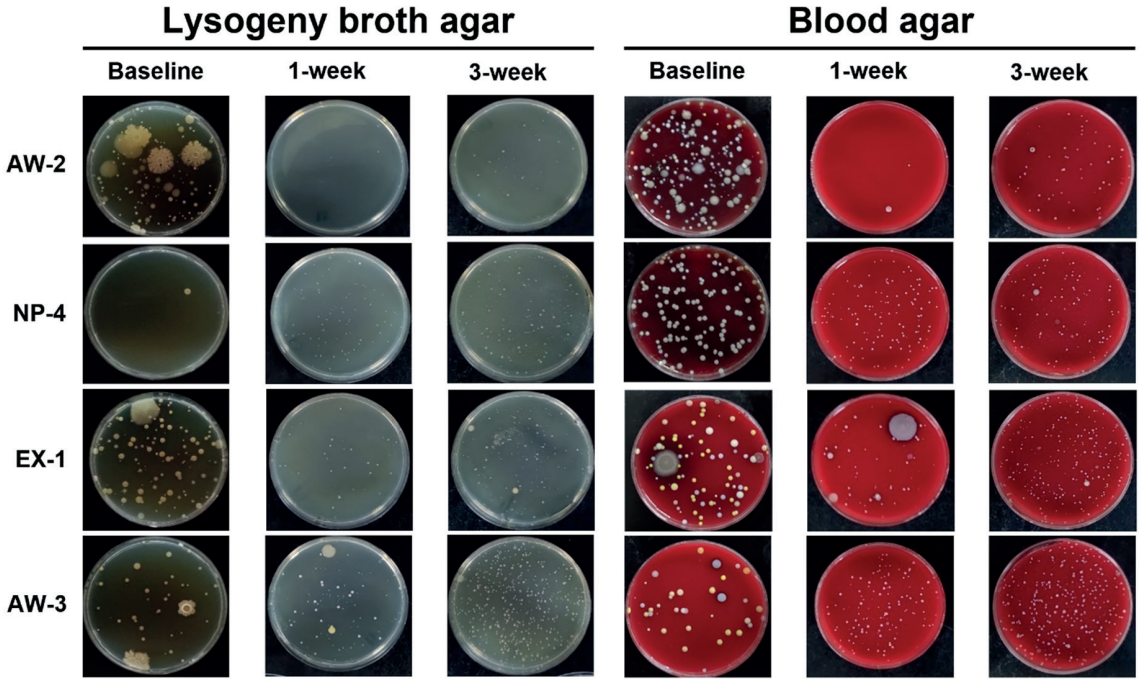

Figure 2. Bacteria cultured on lysogeny broth agar or blood agar sampled from equipment surfaces with or without infection control. AW: high-frequency chest wall oscillation device; NP: negative pressure ventilator; EX: exercise training equipment.

use of ultraviolet light, photocatalysts, and metal ions [51]. Different physical antibacterial methods employ differing mechanisms to exert long-lasting antibacterial effects. Proper fixation of nanometal-derived antibacterial agents reduces the likelihood of their detachment and can prevent cytotoxicity and allergic reactions [51].

Surface and instrument cleaning is a common and effective approach for maintaining environmental hygiene in hospitals [52]. However, modern medical devices often have a large touchscreen, which can be sensitive to certain chemical disinfectants and be damaged in the cleaning process [53]. Although disinfectants designed for touchscreen devices are now commercially available, expecting healthcare workers to be familiar with the compatibility of each disinfectant with every device is impractical. The increasing prevalence of touchscreen-based medical equipment, along with the growing variety of disinfectants, makes it challenging to establish universal guidelines. Additionally, given their demanding clinical workload, healthcare workers have limited time to learn and recall the appropriate disinfectant for each device.

A survey conducted in five intensive care units in Iran revealed that 76% of computer keyboards and electronic equipment were contaminated with bacteria and fungi [45]. This problem can be addressed by using plastic bags or plastic foil to reduce microbiological contamination of these devices [54, 55]. During the coronavirus disease 2019 pandemic, the Polish Medical Society of Radiology suggested that keyboards and X-ray machines be wrapped in transparent plastic bags or plastic foil, which could then be discarded after each examination [55, 56]. Additionally, health-care workers can wrap their mobile phones in plastic bags and regularly sanitize them with 75% alcohol to decrease the risk of contamination [57].

A plastic bag or foil serves as a protective barrier on medical and electronic devices, akin to the role played by gloves in hand hygiene practices. This approach is convenient, cost-effective, and significantly reduces the risk of contamination and transmission of pathogens from these devices [54, 57]. Furthermore, ZnO tape creates a nonporous surface, enhancing protection and enabling health-care workers to clean equipment without risking damage. Implementing this

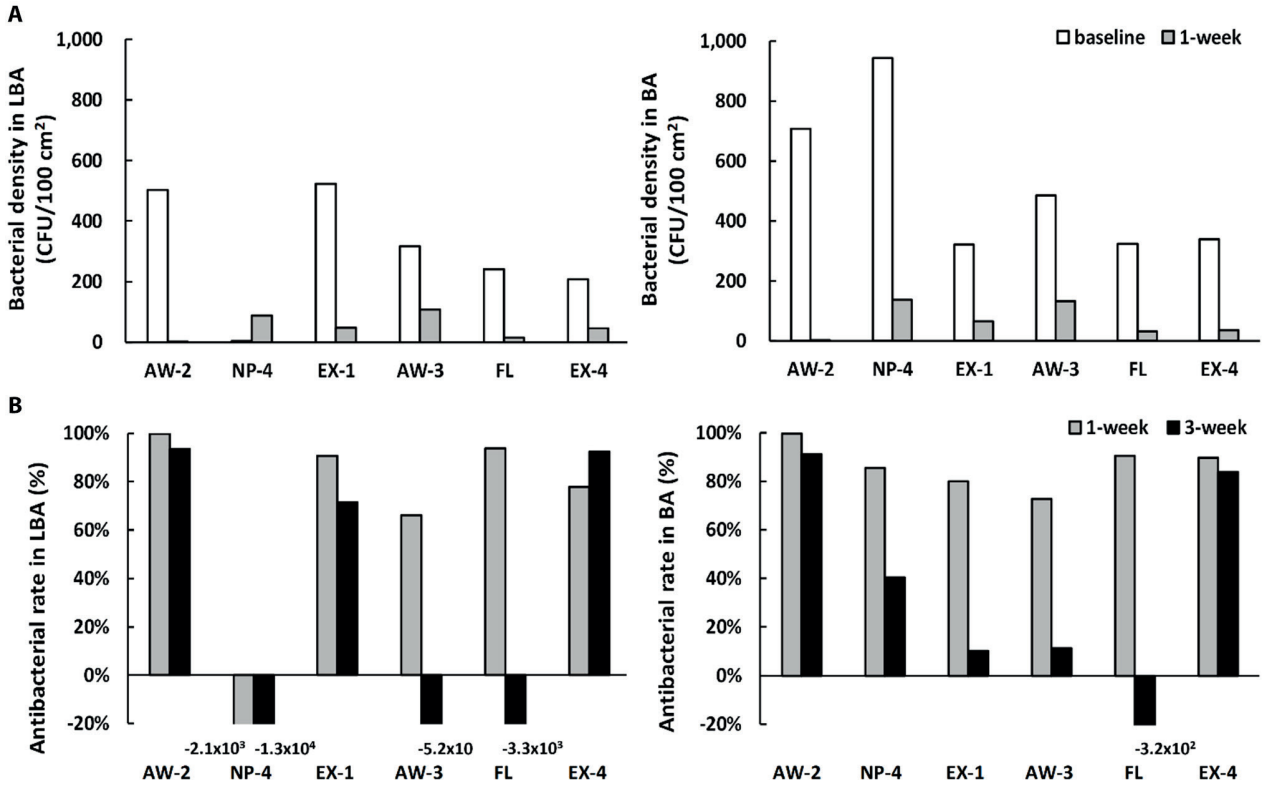

Figure 3. Bacterial count and antibacterial rate on lysogeny broth agar (LBA) or blood agar (BA). (A) Bacterial count at baseline and 1 week after implementation of the antimicrobial strategy. (B) Antibacterial rate at 1 week and 3 weeks after implementation of the antimicrobial strategy. AW: high-frequency chest wall oscillation device; NP: negative-pressure ventilator; EX: exercise training equipment; FL: floor.

approach can help maintain a clean and hygienic environment in the hospital setting, minimizing the risk of pathogen transmission. ZnO tape and nanoparticle suspensions operate on the basis of similar concepts and have similar advantages to plastic bags. They are easy to install, prevent direct contact, and can easily be replaced when contaminated or damaged.

A bacterial biofilm is a thin layer formed by a community of microorganisms that aggregate on the surface of an object, along with the extracellular matrix secreted by these microorganisms [58]. This matrix is primarily composed of polysaccharides, proteins, and DNA [59]. The formation of a biofilm is a complex process involving five main stages: attachment, proliferation, aggregation, maturation, and detachment [60, 61]. Biofilm reduces the effectiveness of antibiotics, making it a crucial factor in antimicrobial strategies. Zinc oxide may help disrupt biofilm formation.

According to statistics from the CDC, surgical site infections account for the highest proportion of nosocomial infections (43%), with *Escherichia coli* being the most common pathogen, accounting for nearly 18% of infections, followed by *S. aureus*, accounting for 12%, and *Klebsiella pneumoniae*, accounting for 9% [62, 63]. According to statistics from the Taiwan CDC, the three most common bacterial infections in intensive care units, regardless of site, are caused by *K. pneumoniae, E. coli,* and *Enterococcus faecalis* [64]. *S. aureus* is also one of the standard bacteria responsible for nosocomial infections, and various drug-resistant strains of it have developed, such as methicillin-resistant *S. aureus* [65]. *K. kristinae* followed by *S. haemolyticus* were the most abundant bacteria in the environment of the pulmonary rehabilitation center in the present study. *S. haemolyticus* is a coagulase-negative species of staphylococci, a member of the human skin flora, and often associated with opportunistic infections [66].

These infections can be localized or systemic and are frequently linked to the insertion of a medical device. *S. haemolyticus* is known for its highly antibiotic-resistant phenotype, and its biofilms are particularly refractory to antibiotics [67]. *K. kristinae* is a common oral and skin microbe in humans that causes opportunistic infections in immunocompromised patients [68].

The application of ZnO tape to touchscreens and device surfaces is a simple yet effective antimicrobial strategy, with the tape acting as a protective barrier between the devices and external environment. This approach not only reduces the need for frequent cleaning and disinfection, but also enables the use of 75% alcohol without risking damage to the devices. Infection control in pulmonary rehabilitation units is underreported in the literature. Further studies should investigate various disinfection strategies to enhance infection control practices in this setting.

This study has certain limitations. First, this was a single-center study with a small sample, which may restrict the generalizability of the findings to other pulmonary rehabilitation centers. Second, the study could not control for variations in personal hygiene practices among respiratory therapists and in the frequencies at which each device was used.

Conclusions

This study demonstrated that ZnO tape and nanoparticle suspensions effectively reduced bacterial contamination on the surfaces of devices in a pulmonary rehabilitation center. These antimicrobial barriers provide durable protection and enable easy cleaning without damage to equipment. Our findings emphasize the need for regular disinfection and innovative strategies to improve infection control in clinical settings for which insufficient data have been reported. Future research should further explore and refine these methods to enhance infection control practices.

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