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Design and Performance Evaluation of a Digital Chlorinator for Domestic Wastewater Disinfection in Healthcare Facilities

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Domestic wastewater from healthcare facilities such as hospitals, community health centres, and polyclinics contains organic loads, toxic chemical compounds, and pathogenic microorganisms that have the potential to cause environmental pollution and pose a risk to public health if not treated adequately. Various conventional treatment methods, including UV, ozonation, aeration, and biofiltration, have been used to reduce pollutants, but cost limitations, high energy requirements, and technical reliability make chlorination the preferred option because it is relatively inexpensive, easy to implement, and produces disinfectant residues that provide continued protection. However, uncontrolled use of chlorine can lead to excessive residues, disinfection by-products (DBPs), and operational inefficiencies. To address these challenges, this study aims to design and evaluate the performance of a digital chlorinator equipped with an automatic control system with dual energy source flexibility (AC/DC and solar panels). This study used a one group pre-test and post-test design with domestic wastewater samples from hospitals, health centres, and polyclinics in Magetan Regency. The water quality parameters analysed included pH, BOD, COD, ammonia, chlorine demand, residual chlorine, and total coliforms. Initial measurements showed BOD of 105–145 mg/L, COD of 198–260 mg/L, ammonia of 13–18 mg/L, and total coliform of 8.5×10^5 to 1.2×10^6 MPN/100 mL, far above the national quality standards. After treatment using a digital chlorinator with an optimum dose of 200 ppm, BOD decreased by 77–82%, COD by 72–78%, ammonia by 75–80%, and total coliforms by more than 99%, while the pH remained stable in the range of 7.1–7.3 and the chlorine residue was maintained at 0.2–0.5 mg/L according to the recommended standard. A comparison of energy sources showed that the effectiveness of solar cells was almost equivalent to that of AC/DC, with a small difference in the reduction of BOD and COD that was not statistically significant. The results of this study conclude that digital chlorinators are effective, adaptive, and have the potential to be an innovative solution in improving the quality of domestic waste treatment in health facilities, especially in areas with limited access to electricity, and can support the achievement of sustainable environmental health goals.

Keywords: Digital chlorinator, Wastewater disinfection, Solar energy, Healthcare facilities

INTRODUCTION

Mercury can naturally occur in various environments, including deserts, oceans, soil, and volcanic activity. Anthropogenic sources, such as fossil fuel combustion, non-ferrous metal production, cement manufacturing, gold mining, and coal burning, also contribute significantly to global mercury emissions (Sari et al., 2022). Naturally occurring mercury, primarily stored in the Earth's crust, is released through geological processes like rock weathering and volcanic activity. These natural emissions, along with human-induced sources, accumulate in the upper layers of the environment, where they interact with vegetation, soil, and water surfaces. Historical mercury emissions are often re-released due to land-use changes, biomass burning, meteorological conditions, and gas exchange mechanisms at the air-surface interface (Arsyad et al., 2022).

Mercury exposure occurs through inhalation, skin contact, and consumption of contaminated fish or aquatic products. (Makahenggang et al., 2022) Organic mercury compounds, capable of crossing cellular membranes, bioaccumulate in freshwater fish at highly toxic levels (Hertika & Putra, 2019). This poses a significant risk in the food chain, as heavy metals, including mercury, inevitably reach humans via dietary intake. In contaminated industrial or mining areas, individuals may inhale mercury vapor, which is absorbed through the lungs into the bloodstream and distributed to organs like the kidneys, liver, and brain. Direct skin contact with mercury or its compounds also facilitates absorption, although less effectively than inhalation or ingestion (Indah & Norsita Agustina, 2020). Excessive mercury exposure beyond tolerable limits can lead to poisoning (Lensoni, Nurdin, 2023).

Prolonged mercury exposure can lead to various health issues, including neurological disorders, immune system problems, kidney damage, and risks to fetal development during pregnancy (Nuraini et al., 2023). Neurological disorders are categorized into acute and chronic conditions. Acute symptoms include headaches, hearing loss, loss of smell, somatosensory disturbances, dysarthria, and occasional emotional instability. Chronic conditions involve tremors, cerebral ataxia, numbness in the lips, hands, and fingers, memory loss, somatosensory disturbances, visual impairments, and insomnia (Kamil & Karma, 2022). Mercury exposure can also result in brain damage, cerebral palsy, motor nerve disorders, and mental retardation. Gold miners and workers in mineral processing industries frequently encounter mercury exposure, adversely affecting their health. In children, mercury exposure can lead to behavioral and cognitive disorders. (Nuraini et al., 2023) In men, particularly with exposure to inorganic mercury, it can cause impotence and reduced libido, while in women, it may disrupt menstrual cycles (Hidayat, 2020).

Observation results show that gold processing activities in the UPTD Ujung Padang Rasian Health Center work area are still mostly carried out using traditional methods. One of the main techniques used is amalgamation, which is a method of binding gold particles using mercury. Although this technique is effective for separating gold, its use carries serious health risks due to the highly toxic nature of mercury. In addition, field observations show that workers generally carry out this activity without using adequate personal protective equipment (PPE), such as gloves, masks, or protective clothing. The absence of PPE makes workers more susceptible to mercury exposure, either through inhalation of mercury vapor, direct contact with the skin, or the possibility of ingesting contaminated particles. Continuous exposure to mercury without adequate protection can cause various acute and chronic health impacts, especially disorders of the nervous system and kidneys. This condition emphasizes the importance of immediate intervention through the provision of PPE, health education regarding occupational hazards, and promotion of safer gold mining methods to reduce the risk of mercury exposure.

Based on this background, this study was designed to answer questions about the demographic characteristics of traditional gold mining workers in the working area of the Ujung Padang Rasian Health Center UPTD, what symptoms of disease are experienced due to mercury exposure, and how is the relationship between demographic characteristics (age, gender, education, and length of service) with the symptoms of disease that appear. The purpose of this study was to analyze the demographic characteristics of workers, identify symptoms of disease due to mercury exposure, and assess the relationship between demographic factors and symptoms of disease in traditional gold mining workers in the area. Wastewater produced by healthcare facilities such as hospitals, community health centres and polyclinics contains a complex mixture of organic materials, nutrients, pharmaceutical compounds, heavy metals and pathogenic microorganisms, which has the potential to cause environmental pollution and pose a risk to public health if not managed properly (Yuan & Pian, 2023). Hospital wastewater is consistently reported to have concentrations of BOD, COD, TSS, ammonia, and pharmaceutical contaminants that often exceed discharge quality standards. If released into receiving bodies without adequate treatment, this can cause eutrophication, toxicity to aquatic organisms, and disruption to surface water quality and groundwater sources (Boutros et al., 2025) .In addition to chemical and organic pollution, the microbiological aspects of wastewater from healthcare facilities are a major concern due to the presence of pathogenic bacteria, viruses, and antibiotic-resistant bacteria that can survive in the aquatic environment and pose a risk of disease transmission to workers, patients, and the surrounding community (Yuan & Pian, 2023). The COVID-19 pandemic has increased the urgency of healthcare facility waste treatment because traces of viral genetic material, including SARS-CoV-2 RNA, have been detected in wastewater streams, triggering the need to ensure reliable disinfection stages in hospital waste treatment systems (Achak et al., 2021). Therefore, healthcare facility waste treatment protocols must include a combination of processes capable of reducing organic load, removing pharmaceutical compounds, and ensuring the inactivation of pathogenic microorganisms prior to discharge into the environment (Mousazadeh et al., 2022)

Various wastewater treatment technologies for healthcare facilities have been developed and tested, including biological processes such as activated sludge and membrane bioreactors, which are effective in reducing BOD and COD. However, in many cases, further treatment is required to ensure microbiological sanitation and the removal of micro-pollutants (Boutros et al., 2025). Constructed wetlands or artificial wetland systems have been promoted as a low-cost solution capable of reducing physical-chemical and some microbiological parameters through biological mechanisms and filtration, but their effectiveness depends on the design, hydraulic retention time, and local climate, often requiring an additional disinfection stage (Mousazadeh et al., 2022). Advanced disinfection technologies such as ultraviolet (UV) light, ozonation, and advanced oxidation processes (AOP) demonstrate high performance in inactivating microorganisms and degrading persistent organic compounds, but these technologies generally require high energy, higher initial investment and operating costs, and more complex technical control (Mousazadeh et al., 2022). On the other hand, chlorination (the addition of chlorine or calcium hypochlorite) remains a widely used disinfection method due to its relatively low cost, ease of application, and ability to produce persistent disinfectant residues that provide post-treatment protection. However, its use also poses challenges in the form of the formation of disinfection by-products (DBPs) and the potential selection of tolerant bacteria (Lindmark et al., 2022).

Several applied studies indicate that on-site chlorination in hospital wastewater treatment systems can effectively reduce the number of indicator organisms and pathogens when the dosage, contact time, and water conditions are properly controlled. However, these studies also highlight the need for precise dosage control to avoid excessive residues and the formation of harmful DBPs (Amin et al., 2024). In addition, other studies warn that uncontrolled chlorination can affect the composition of waste microbiota and potentially increase the frequency of enzyme-producing bacteria (e.g. ESBL), making dosage management and monitoring important aspects in the application of chlorination in healthcare facilities (Rolbiecki et al., 2022). In this context, disinfection solutions that combine the reliability of chlorination with automatic control and renewable energy sources are particularly attractive for healthcare facilities, especially in developing countries or locations with unstable electricity supplies (Boutros et al., 2025).

Advances in digital technology and smart control in the water treatment sector show great potential for improving the accuracy of chemical dosing, real-time monitoring of residual disinfectants, and optimising operations through control algorithms or machine learning (Q. Li et al., 2024). The implementation of automated systems and sensors that can adjust chlorine dosage proportionally to flow rate and chlorine demand can reduce manual intervention, lower the risk of overdosing, and maintain residual chlorine within a safe yet effective range for inactivating pathogens (Lindmark et al., 2022). In addition, the integration of solar energy sources (solar cells) in the disinfection unit enables continuous operation in remote locations or during power outages, thereby reducing dependence on conventional AC power supplies and increasing the resilience of the waste treatment system (Chu et al., 2019). Several early implementations of solar-powered systems incorporating on-site chlorine generation technology have been reported for community drinking water, demonstrating that solar-powered solutions can provide reliable automatic dosing when properly designed (Chu et al., 2019).

However, a recent literature review identified significant gaps in research and practice related to automated chlorination for healthcare facility wastewater; firstly, most studies focus on the effectiveness of disinfection methods in general or on specific parameters, while the development of digital chlorinators that combine automatic control, residual monitoring, and AC/DC plus solar operational capabilities is still very limited (Bhandari et al., 2023). Secondly, there is little research that comprehensively tests the design of chlorinator devices (hardware and control software) under real conditions of complex hospital waste, including integrated measurements of pH, BOD, COD, ammonia, and total coliform, which are indicators of the success of the disinfection process and the quality of the output (Boutros et al., 2025). Thirdly, important aspects such as the resistance of electronic components to corrosive chlorine gas conditions, waste load variations, flow rate fluctuations, performance comparisons between AC and solar energy sources, and the risk of DBP formation in the context of hospital waste have not been systematically analysed (Parveen et al., 2022). Therefore, there is a need for research that combines tool design engineering, laboratory and field performance evaluation, and environmental and health risk analysis to ensure solutions that are not only effective but also safe and feasible to implement in the context of healthcare facilities (Mousazadeh et al., 2022).

Based on these issues, this study aims to design and evaluate the performance of a digital chlorinator capable of operating on dual energy sources (AC/DC electricity and solar panels), equipped with automatic dose control and chlorine residual monitoring, and tested on domestic wastewater samples from hospitals, health centres, and polyclinics to assess its effectiveness on key water quality parameters: pH, BOD, COD, ammonia, and total coliform. The performance assessment will include controlled laboratory tests and field studies to test the operational stability of the device under real fluctuating conditions, evaluation of residues and the possibility of DBP formation, as well as a comparative analysis of the efficiency between grid-based and solar-based operations. Thus, this research is expected to provide technical contributions in the form of practical device designs, safe operational protocols, and empirical evidence regarding the feasibility of using digital chlorinators as part of a sustainable and resource-constraint-responsive healthcare facility waste management strategy.

METHOD

Research Design

This study is an experiment with a *one group pre-test and post-test* design, which is used to evaluate the effectiveness of digital chlorinators in disinfecting domestic wastewater from health facilities. This design allows for the measurement of wastewater quality before and after treatment, so that the effect of chlorine dosage on the tested water quality parameters can be analysed.

Location and Samples

Wastewater samples were obtained from the Wastewater Treatment Plant (WWTP) of Dr. Sayidiman Hospital in Magetan, several community health centres, and polyclinics in Magetan Regency. To ensure diversity of conditions, the study was also conducted at the Sanitation Study Programme workshop, Surabaya Ministry of Health Polytechnic, Magetan Campus. The wastewater used was the output of the primary treatment unit, which still contained high levels of organic and microbiological loads.

Tools and Materials

The main device developed is a digital chlorinator designed to operate on both AC and DC currents. The main components include a stabiliser converter, a dry battery/accumulator, a digital control switch internet system, a double membrane pump, a solar cell panel, a digital current voltmeter, a digital display debit control, *automatic water level*, and *water level Cl2 probe*. The disinfectant used is chlorine tablets with a minimum active chlorine content of 80%, as well as supporting equipment such as pipes, centrifugal pumps, valves, and a digital chlorine solution flow control system.

Research Procedure

The research began with the assembly and testing of the chlorinator device in the laboratory to ensure the functionality and stability of the system. This was followed by field trials, in which chlorine solution was fed into the wastewater stream at varying chlorine solution flow rates of between 0.8 and 1.6 ml/s. The chlorine concentrations tested ranged from 50 to 300 ppm with a chlorine solution flow rate of 50 to 200 ml/minute.

Wastewater samples were analysed for pH, BOD, COD, ammonia, chlorine demand, residual chlorine, and total coliform parameters. Measurements were taken before treatment (control/blank) and after treatment with the determined optimum dose. Laboratory tests were conducted in accordance with the standards of Minister of Environment Regulation No. 68 of 2016 concerning Domestic Wastewater Quality Standards.

Data Analysis

The data from the water quality parameter measurements were analysed by comparing the values before and after treatment, as well as against the applicable quality standards. The reduction efficiency was calculated as a percentage for each parameter. The test results were analysed descriptively and quantitatively to describe the performance of the digital chlorinator, while the optimum dose was determined based on the maximum effectiveness of the reduction in organic and microbiological parameters, taking into account the availability of residual chlorine in accordance with standards.

RESULT AND DISCUSSION

Initial Characteristics of Wastewater

Initial measurements of wastewater samples from hospitals, community health centres, and polyclinics showed that almost all water quality parameters exceeded the quality standards set by Minister of Environment Regulation No. 68 of 2016. Initial BOD values were recorded between 105–145 mg/L, COD between 198–260 mg/L, ammonia 13–18 mg/L, and total coliforms reached 8.5×10^5 to 1.2×10^6 MPN/100 mL. Meanwhile, the pH was relatively neutral, ranging from 6.8–7.0. These conditions confirm that domestic wastewater from health facilities still requires further treatment, particularly disinfection.

Effectiveness of Water Quality Parameter Reduction

After treatment with a digital chlorinator using chlorine tablets, there was a significant decrease in wastewater quality parameters. Test results showed that BOD decreased by an average of 77–82%, COD decreased by 72–78%, and ammonia decreased by approximately 75–80%. Meanwhile, total coliforms decreased by more than 99%, indicating that the digital chlorinator system is effective in inactivating microorganisms. The pH value remained stable in the range of 7.1–7.3 after treatment, indicating that the use of chlorine at controlled doses did not cause extreme changes in acid-base conditions.

Residual Chlorine and Calcium Hypochlorite Requirements

Chlorine residue measurements show that at an optimum dose of 200 ppm, the residual chlorine remains in the range of 0.2–0.5 mg/L. This figure is in line with the required standard recommendation, which is to maintain sufficient chlorine residue to ensure safety without causing negative effects. These results also confirm that the use of a digital control system on the chlorinator is capable of regulating the dosage with precision, thereby achieving disinfection efficiency without producing excessive residues.

Performance Comparison with AC/DC Power Sources and Solar Cells

Field tests were also conducted by comparing AC/DC and solar cell power sources. The results showed that both were relatively equally effective. When using solar cells, the effectiveness of reducing BOD, COD, and ammonia was slightly lower (77–80%) compared to AC/DC (80–85%), but the difference was not statistically significant. In terms of microbiological parameters, both showed high effectiveness with a total coliform reduction of more than 99%. This proves that digital chlorinators can be operated well using solar energy, making them suitable for health facilities in areas with limited electricity.

Table 1.

Changes in Wastewater Quality Parameters Before and After Treatment with the Digital Chlorinator

Parameter	Hospital (Before)	Hospital (After)	Primary Health Center (Before)	Primary Health Center (After)	Clinic (Before)	Clinic (After)	Average Removal Efficiency (%)
pH	6.9	7.2	7.0	7.3	6.8	7.1	Stable
BOD (mg/L)	145	32	120	28	105	26	77–82
COD (mg/L)	260	70	215	64	198	55	72–78
Ammonia (mg/L)	18	4	15	3	13	3	75–80
Total Coliform (MPN/100 mL)	1.2×10^6	1.5×10^2	9.8×10^5	1.2×10^2	8.5×10^5	9.5×10^1	>99

Table 1 illustrates the gender distribution of the respondents, with 36 participants (92.3%) being male and 3 participants (7.7%) being female. The age distribution indicates that 9 respondents (23.1%) fell within each of the age categories of 26-35 years, 36-45 years, and 46-55 years. Five respondents (12.8%) were aged 17-25 years, while 3 respondents (7.7%) each were in the age groups of 56-65 years and above 65 years. Additionally, 1 respondent (2.6%) was aged 12-16 years. The educational background of the respondents shows that 16 participants (41%) had completed elementary school, 11 participants (28.2%) had a junior high school education, and 10 participants (25.6%) had finished senior high school. Only 2 participants (5.1%) had attained a bachelor's degree. Regarding work duration, 26 respondents (66.7%) had been employed for less than 5 years, while 9 respondents (23.1%) reported a work history of 5-10 years. Four respondents (10.3%) had worked for 11-15 years. Table 1 shows that the use of digital chlorinators has a significant impact on improving the quality of domestic wastewater from hospitals, community health centres, and polyclinics.

The BOD parameter, which was originally in the range of 105–145 mg/L, was successfully reduced to 26–32 mg/L, with an efficiency of 77–82%, while COD, which initially reached 198–260 mg/L, fell to 55–70 mg/L with an efficiency of 72–78%. Ammonia concentrations also decreased sharply from 13–18 mg/L to 3–4 mg/L, equivalent to an efficiency of 75–80%. The most notable effectiveness was seen in microbiological parameters, where total coliforms, which initially ranged from 8.5×10^5 to 1.2×10^6 MPN/100 mL, decreased by more than 99% after treatment, demonstrating the system's strong ability to inactivate pathogenic organisms. Interestingly, the pH value remained stable in the neutral range (6.8–7.3), so there were no extreme changes in the chemical conditions of the water. These results confirm that digital chlorinators are not only capable of reducing organic and chemical parameters but are also highly effective in microbiological disinfection, while maintaining the chemical stability of wastewater, making them a practical and adaptive technology for healthcare facility wastewater treatment.

The results of the study indicate that the designed digital chlorinator is capable of significantly reducing organic load (BOD and COD) and ammonia, as well as reducing total coliforms by more than 99%, making this device effective as a final disinfection stage for domestic wastewater from healthcare facilities. These results are consistent with a literature review reporting that the application of chemical disinfection in hospital wastewater treatment units can substantially reduce microbiological indicators when the dosage and contact time are properly controlled (Liu et al., 2023). The decrease in BOD and COD recorded in this study is most likely a combination of the effects of chlorine oxidative residues on dissolved organic matter and the reduction of some particulate fractions through flocculation and post-treatment sedimentation, a mechanism that has been reported in studies on clinical waste treatment (Majumder et al., 2021).

The stability of the pH after treatment, which remained within the neutral range, indicates that digitally controlled chlorine dosing prevents the extreme acid-base changes that are often a concern in uncontrolled chlorination applications, thereby reducing the risk of corrosion and biological interference downstream (T. Li et al., 2022). Automatic dosage control using flow sensors and digital controls, as implemented in the prototype, improves dosing precision and reduces chlorine residue variation often encountered in manual applications, in accordance with the principles of smart disinfectant management systems recommended in the smart water systems literature (Mahmodian et al., 2024).

The measurement of average chlorine residuals within the safe range in this study supports the guidelines of the WHO and other health agencies that recommend a minimum residual free chlorine (e.g. ≥0.5 mg/L under certain conditions) to ensure post-treatment protection, although target values may vary depending on the purpose (drinking water vs controlled disposal) (Organization, 2020). It is important to note that during the pandemic, some authorities temporarily increased the residual chlorine target in wastewater output to mitigate the risk of viruses, but this measure must be balanced with the risk of disinfection by-product (DBP) formation and environmental impact (T. Li et al., 2022).

Concerns regarding the formation of DBPs during chlorination are widespread and well documented in recent studies; therefore, chlorinator operating protocols should include DBP measurements (e.g., THMs, HAAs) and mitigation strategies such as controlling the minimum effective dose and pre-removing organic precursors to suppress DBP formation (Kalita et al., 2024). In addition to the DBP aspect, several studies indicate that chlorination can alter the composition of the microbiome and increase the proportion or selection of certain resistant bacteria; therefore, monitoring the resistome and microbiome post-disinfection should be considered in the long-term evaluation of applications in healthcare facilities (Rolbiecki et al., 2023).

A comparison of the performance between AC/DC-based operation and solar panels shows that solar-based operation can provide almost equivalent disinfection effectiveness for microbiological parameters, although it is slightly lower for most organic removal; these findings support the literature assessing the feasibility of renewable energy-based solutions in small to medium-scale disinfection units, especially in contexts with limited electricity networks (Anker et al., 2025). The solar energy approach is also in line with the growing trend of solar-driven treatment technology and off-grid solutions, but its success in the field depends on panel dimensions, battery capacity, and energy management to maintain a stable supply during weather variations (Roy & Messaddeq, 2024).

Technical analysis of pump performance and chlorine solution discharge shows that variations in discharge head reduce actual discharge slightly (a small percentage decrease), which is important to consider when performing digital dosing calibration; this small decrease is consistent with the characteristics of membrane and centrifugal pumps, which are affected by head height and solution viscosity (Yang et al., 2024). Therefore, the pump specifications and control loop must be calibrated under field conditions (actual head and temperature) to ensure the necessary dosing accuracy to achieve the target chlorine residue without wasting chemicals (Yang et al., 2024).

The main strength of this research is the integration of hardware engineering aspects (prototype design), digital control (monitoring of discharge and residual), and comprehensive water quality parameter testing (pH, BOD, COD, ammonia, total coliform) on real samples from several health facilities, thus providing empirical evidence of the technical feasibility of digital chlorinators (Majumder et al., 2021). The limitations of the study include the lack of specific DBP measurements and post-disinfection resistome analysis, as well as the limited number of test locations; these issues are important to explore in further studies in order to understand the long-term environmental health implications (Kalita et al., 2024).

For field-scale implementation and adoption in healthcare facilities with limited resources, practical recommendations include adding a DBP measurement module to testing protocols, strengthening automated monitoring (calibrated residual chlorine sensors, flowmeters), developing dosage SOPs based on actual flow rates, and conducting cost-benefit studies comparing conventional AC/DC operations with solar-assisted scenarios in terms of total cost of ownership (TCO). In addition, training of operational personnel and integration of preventive maintenance mechanisms are necessary to minimise downtime and maintain long-term dosing accuracy.

CONCLUSION

This study shows that the designed digital chlorinator is capable of significantly reducing BOD, COD, ammonia, and total coliform and can be operated with AC/DC power sources or solar panels with microbiological effectiveness >99%. For wider application, it is recommended that DBP and resistome measurements be added in further studies, along with pump calibration and control under field conditions, as well as an economic evaluation of solar-assisted implementation to ensure that this solution is safe, effective, and sustainable. This study recommends that the application of digital chlorinators in healthcare facilities be further developed to include analysis of disinfection by-products (DBPs) and microbial resistance to ensure long-term safety, as well as larger-scale multi-site trials to assess effectiveness under various waste load conditions. in addition, the use of solar panels as an alternative energy source should be considered as they have been proven to be equivalent to AC/DC electricity, but an evaluation of long-term ownership costs is still necessary, so the integration of automatic sensor systems, routine calibration, and technical staff training are important steps to ensure the sustainability, efficiency, and readiness of this technology as a solution for domestic wastewater treatment in healthcare facilities.

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