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Infection

The impact of comprehensive air purification on patient duration of stay, discharge outcomes, and health care economics: A retrospective cohort study

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A R T I C L E I N F O

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A B S T R A C T

Background: Infectious airborne and surface pathogens constitute a substantial and poorly explored source of patient subclinical illness and infections. With that in mind, a system of advanced air purification technology was designed to destroy the DNA and RNA of all bacteria, fungi, and viruses. This study compares the effects of advanced air purification technology versus high efficiency particulate air filtration with respect to certain metrics of health care economics and resource utilization at a large, community-based, urban hospital. Our hypothesis was that the use of the advanced air purification technology would decrease health care durations of stay, lead to fewer nonhome discharges, and decrease hospital charges.

Methods: After the installation of advanced air purification technology, 3 resultant air purification "zones" were established: zone C, a control floor with high efficiency particulate air filtration; zone B, a mixed high efficiency particulate air and advanced air purification technology floor; and zone A, a comprehensive advanced air purification technology remediation. This study included nonbariatric surgical patients admitted to any zone between December 2017 and December 2018, with reported case mix index on discharge. We analyzed hospital duration of stays, discharge destination, and hospital charges with adjustment for severity of illness using the case mix index. The likelihood of mortality, health care-associated infection, and readmission for each study zone was examined using logistic regression adjusting for case mix index, age, sex, and source of admission.

Results: The study included 1,002 patients across the 3 zones, with mean age of 55.8 years (53.7% female), average case mix index of 1.98, and mortality of 1.7%. Compared with zone C, patients in zones A and B demonstrated decreased hospital stays, a greater percentage of home discharges (86.5–87.8% vs 64.7%), and less hospital charges. In addition, logistic regression modeling performed on 999 study patients showed that the likelihood of mortality, hospital-acquired infections, and readmissions did not differ among the 3 zones. A trend toward a lesser incidence of hospital-acquired infections was noted in zones A and B (0.40% and 0.48%, respectively) when compared with zone C (0.63%).

Conclusion: Patients in the advanced air purification technology zones demonstrated statistically significant improvements in durations of stay, discharge to home, and costs after adjusting for case mix index. In addition, a trend toward fewer hospital-acquired infections in advanced air purification technology zones was noted. These findings suggest that environmental factors may affect key clinical and economic outcomes, supporting further research in this important and largely unexplored area.

Introduction

According to the Centers for Disease Control and Prevention, more than 1.7 million people contract a hospital-acquired infection (HAI) each year,[1] with 100,000 attributable deaths and estimated health care costs of between $35 to $88 billion.[2,3] The approximate

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per-hospitalization economic burden for an HAI ranges from $17,070 to $32,176.[4] Beginning in August 2007, HAIs have been included by the Centers for Medicare and Medicaid Services on the list of "never events" that are no longer covered by insurance.[5] Consequently, the added costs of HAIs are borne directly by the hospital.

Infectious bacteria, fungi, and viruses in hospitals may cause subclinical infections (SUBI).[6] The incidence of SUBIs is difficult to quantify because these infections are not monitored unless an outbreak occurs or a positive culture is identified. Infections involving multidrug-resistant bacteria and invasive fungal infections are known sources of recent outbreaks.[7−9] In addition to greater monetary costs, the presence of SUBIs and HAIs within the hospital setting have a potentially negative impact on health care length of stay (HLOS) or discharge destination.[10−13] Still, the general area of SUBIs remains largely neglected and unexplored.

Traditional efforts for decreasing HAIs focused on strategies to eliminate the pathogens present on the patient, clinical surfaces, and health care workers.[14] These efforts led to the implementation of various protocols of infection control and sterilization that have decreased HAI rates successfully.[15] Yet, despite the focus on surface pathogens, recent literature shows that a large portion of HAI-generating pathogens are airborne.[16] Previous experience with the advanced air purification technology (AAPT) demonstrated that comprehensive remediation of airborne pathogens resulted in a decrease in infectious fomites across a variety of patient-facing surfaces.[17]

The AAPT used in this study is more efficient than most current methods of air filtration in the hospital setting.[18] Operationally, the AAPT replaces a section of the hospital's existing heating ventilation and air conditioning ductwork and utilizes ultraviolet, germicidal irradiation technology and a multireflective enclosure to provide continuous, real-time remediation of all airborne pathogens before the air entering areas of patient care. The AAPT treats all source and recirculated air entering the protected space and is installed downstream of an air handling unit (AHU) with HEPA filtration.

Most currently used approaches to sterilization require that rooms be vacant for sterilization but do not protect against any pathogens that are generated or reintroduced during standard clinical operation.[19−23] Of note, the AAPT uses a continuous, real-time "kill" model that is designed specifically to destroy the DNA and RNA of all bacteria, viruses, and fungi, thus leaving them noninfectious.[24] This model is different than the "capture" model used by HEPA filtration, where captured particulates can continue to grow above and within the matrix of the filter and can reenter the clinical space with continual exposure to air velocity. In addition, fungal spores captured by standard HEPA filtration can release cytotoxic volatile organic compounds (VOCs).[25] The current AAPT system has been tested by the National Homeland Security Research Center and proven to kill the anthrax spore, the most difficult biologic pathogen to effectively neutralize.[26] Accordingly, the AAPT is able to provide a 9-log decrease to comprehensively remediate airborne pathogens, including bacteria or spores (eg, *Clostridioides difficile*, *Streptococcus*, *Pseudomonas*, *Staphylococcus*, *Mycobacterium tuberculosis*, etc), viruses (smallpox, chickenpox, influenza, etc), and fungi (aspergillus, alternaria, cladosporium, etc). The AAPT accomplishes these air purification metrics on a single pass without the generation of any known harmful byproducts, ozone, or intermediate molecules.[18]

The aim of this study was to examine the effect of AAPT on key clinical and economic outcomes compared with standard HEPA filtration. Given that a substantial proportion of infectious surface pathogens originate from the air, the indirect effect would manifest as a decrease in downstream harmful sequelae of a decrease infectious airborne and surface pathogen loading.[17] We hypothesized that a comprehensive remediation of airborne pathogens beyond standard HEPA filtration would positively impact HLOS, post discharge destinations, and overall hospital charges (HC).

Materials and Methods

The present study was deemed exempt by the institutional review board of St. Luke's University Health Network. Our research team evaluated retrospectively 3 air filtration zones located on 2 medical and surgical floors of our urban-based community hospital, with data from December 18, 2017 and December 31, 2018. The first zone was a control floor (zone C) with AHU HEPA remediation. The second zone (zone B) was a portion of an adjacent medical and surgical floor receiving mixed AHU HEPA and AAPT air. The third zone (zone A) included the remainder of that floor and featured exclusive comprehensive AAPT air remediation. Figure 1 illustrates the geographic zones studied and Table I shows the zones evaluated during the study.

The physical and clinical footprint and sun exposures of the 2 floors studied were identical, as seen in Fig 1. The 2 floors were built using similar infrastructure components and construction materials at different times, with zone C being completed before zones A and B. In addition to identical footprints, the staffing and standard operating procedures for nursing care were similar on both floors and across all 3 study zones. Table II shows the staffing characteristics of the 3 areas. Because the study is retrospective in nature, it was not feasible to blind patients or staff. There were also no new major nursing or other direct patient care initiatives implemented on either floor during the study period. The background environmental metrics used by the research team to compare AHU-HEPA and AAPT were published previously and examined prospectively, with detailed methodologic descriptions outlined in a separate manuscript.[17] Of note, the earlier publication evaluated overall airborne bacterial and fungal loading and included microbial testing of 3 commonly touched patient surfaces and 2 commonly touched clinical surfaces, with additional swabbing of air supply diffusers and return vents for viable bacteria and fungi.[17]

The current study was based on a subset of nonbariatric surgical patients with an inpatient admission to any of the 3 zones who had a case mix index (CMI) included in their electronic medical record at the time of discharge ($N = 1{,}002$). CMI is assigned to each inpatient admission using a proprietary algorithm and is a measure of the relative amount of resources that an inpatient within a given Medicare Severity-Diagnosis Related Group will require during their stay. It is a major driver of the payment amount for inpatient admissions. The CMI values are relative to one another and are adjusted each federal fiscal year.[27−30] Table III shows the breakdown of surgical service line by study arm. Patient cohorts and zones were well balanced, with no differences in distribution skewness in all surgical subspecialties except for bariatric operations. Zones A and B had 223 and 238 bariatric patients, respectively, whereas zone C only had 2 such patients. Consequently, meaningful zone comparisons were not possible for bariatric patients, leading the research team to exclude this surgical group. Finally, it was not possible to distinguish elective and emergency operations from the data provided and therefore, "emergency surgery" variable was not able to be included in final analyses.

The flow diagram in Fig 2 shows that the 1-year cumulative admissions to the 3 study zones included 8,255 patients. The research team then excluded patients without a CMI score and unbalanced medicine and bariatric patients (due to skewed distribution between study zones, as determined using sensitivity analyses), bringing the final number of patients analyzed to 1,002. In terms of specific recorded diagnoses, the data did not have sufficient granularity to match cases in a statistically valid manner. The research team therefore, chose to utilize CMI to account for

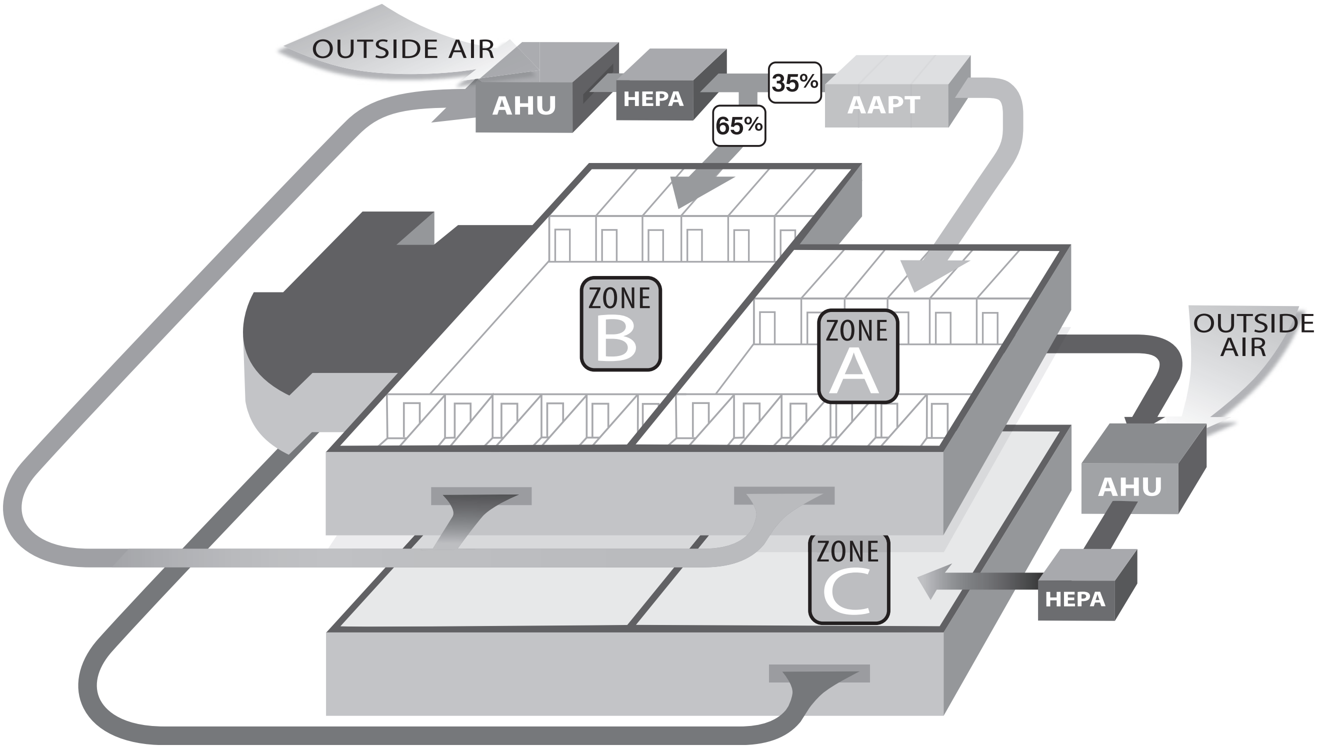

Fig. 1. Schematic representing zones A, B, and C and the existing heating ventilation and air conditioning layout for all zones.

Table I
HVAC design by zone studied

Zone	HVAC design
A	AHU HEPA and AAPT
B	AHU HEPA and return air from Zone A
C	AHU HEPA only

comorbidities, diagnoses, and underlying diseases. CMI was assigned by the hospital and included as a covariate in the statistical analysis.

One-way analysis of variance was used to test differences in HC, patient age, and HLOS between each study arm. χ^2 testing was used for categorical data, including stratified age distribution, sex, race or ethnicity, admitting service, and subservice line(s). Analysis of covariance was used to test differences in charges, emergency department, and admission HLOS while adjusting for CMI between each study arm. Nonparametric tests were used to assess the differences in the medians of charges and HLOS between study arms. Likelihoods of mortality, HAI, and readmission for each study arm were examined using logistic regression adjusting for CMI, age, sex, and source of admission (eg, home versus nursing home). Adjusted odds ratios and 95% confidence intervals (odds ratio, 95% confidence interval) were calculated and reported. Variables that met the statistically significant threshold of 0.20 in bivariate tests were included in the models. Unless otherwise specified significance was set at alpha <0.01 with a 99% confidence interval. All statistical analyses were performed using SPSS 24.0 (IBM, Armonk, NY), and the study was initially powered at 95%. Normalized data for HLOS and HC were indexed using the control floor (zone C) as the reference point and reported along with the corresponding 95% confidence interval. All data were provided by the hospital and analyzed by an independent third-party epidemiologist.

Results

The breakdown of surgical service lines by study arm is presented in Table III, showing that all surgical subspecialties were well balanced with the exception of bariatric operations. The main study results are presented in Table IV. The overall age of the patient sample was 55.8 ± 17.8 years, and 53.7% of the patients were female. With the exception of younger age and greater CMI in zone C, there were no differences in patient demographics among the 3 study zones.

When examining discharge destination, a statistically significantly greater proportion of patients in the AAPT zone (zone A) were discharged home (87.8%) compared with the control zone (zone C; 63.7%). This difference was also reflected in the mixed zone, as 86.5% of these patients were discharged home rather than a facility ($P < .001$). HLOS and HC were compared among the groups by assigning the control group an index value of 1.00 for each factor. Zone A (pure filtration) and zone B (mixed filtration) both had a statistically significant decreases in HLOS (comparative value of 0.605 and 0.624, respectively) when contrasted with the control (AHU-HEPA) group. Likewise, HC were 22.3% and 19.5% less in the pure and mixed filtration patient areas when compared with zone C, evidenced by the indices of 0.777 and 0.805 relative to the control floor index value of 1.00 (Table IV).

Table V presents a summary of the previously published environmental data.[17] This table shows that as the level of environmental purity increased (zone C to B to A), the airborne bacterial, fungal, and VOC level decreased. Likewise, the viable fungi by swab also decreased with increased environmental purity. Viable bacteria by swab was greater in Zone A than zone B but both zones A and B were less than zone C. The presence of surface bacteria in zone A can most likely be attributed to an introduction by a patient or clinical provider because the corresponding air sample showed no bacteria.

Table II
Personnel staffing by zone studied with no major differences in clinical education

Parameter	Zones A and B	Zone C
Age mean	33	36
Sex (% female)	98.3	90.2
Training	BLS, nurse residency program, 8–10 weeks of orientation	BLS, nurse residency program, stroke NIH education, stepdown level of care education, 8–10 weeks of orientation
Dayshift staffing ratio	1:5	1:5
Nightshift staffing ratio	1:6	1:6

BLS, basic life support; *NIH*, National Institutes of Health.

Table III
Surgical service line by study arm

Surgical service line	Zone A	Zone B	Zone C
Bariatric	223	238	2
General surgery	73	82	81
Urology	26	32	26
Colorectal	45	53	46
Orthopedic	66	76	77
Plastic surgery	4	12	4

To evaluate the data for intergroup differences in HAI, mortality, and readmissions, we performed logistic regression adjusting for CMI, age, sex, and source of admission (eg, home versus nursing facility). This was performed owing to observed differences in patient age and CMI among the 3 study groups (Table IV). The research team found that in each of the models, the likelihoods of HAI (OR 1.249; 95% CI, 0.800–1.950); mortality (OR 1.251; 95% CI, 0.975–1.605); and readmission (OR 1.283; 95% CI, 0.996–1.652) were not statistically significant among the 3 study zones. From descriptive perspective, a trend toward lesser frequency of HAIs was noted across AAPT-serviced areas, with HAI incidence of 0.40% for zone A, 0.48% for zone B, and 0.63% for zone C.

Discussion

The present study demonstrates that in the setting of similar layouts of the hospital floors, nursing characteristics and practices, and comparable patient populations, the use of AAPT, either in isolation or in a mixed setting with HEPA-AHU, resulted in a downstream effect of decreased HLOS, fewer nonhome discharges, and lower HC. These are important findings, primarily because airborne pathogen loading, including its relationships to key clinical outcomes and operational parameters, is a largely neglected topic that has not been studied comprehensively. Therefore, the understanding and the appreciation of the role that infectious airborne bacterial, fungal, and viral pathogens play in overall patient wellness continue to be limited.

In a previously published study utilizing the same AAPT design, our research team found that as the degree of air purification increased from zone C to zone B and finally to zone A, the airborne fungal, bacterial, and the levels of VOCs decreased with increased environmental purity (Table V). The decrease in airborne pathogens coincided with a decrease in measured pathogens on commonly touched patient and clinical surfaces as well as return vents.[17] The present study extends these original findings by examining secondary, downstream surrogates of air and environmental purity, presumably owing to the decrease in airborne pathogens, and thus, surface fomites as potential sources of illness.[31–33] One can speculate that elimination of airborne pathogens and thus a decrease in surface pathogen loading may influence downstream factors, such as HAIs, including SUBIs. Such low-grade events may contribute to increased use of health care resources while being interpreted by clinical teams as “atelectasis,” “fevers of unknown origin,” “mild viral illness,” or similar “benign-appearing” manifestations.[34–37]

Figure 3 demonstrates the levels of measured airborne and surface pathogens in each of the 3 study zones over the course of the previously published environmental study.[17] This shows that the air quality in zones B (mixed AHU HEPA and AAPT recirculated air) and

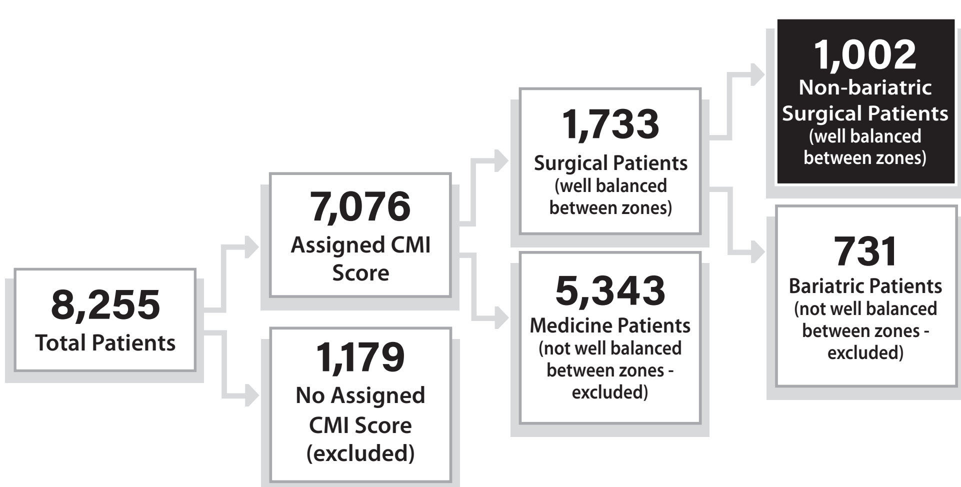

Fig 2. Flow diagram showing total patient breakdown.

Table IV
Unadjusted key patient group characteristics and outcomes by study Zone A, B, and C

Parameter	Zone A (N = 278)	Zone B (N = 343)	Zone C (N = 381)	P value
Mean age (STD)	67.4 (16.1)	60.7 (16.5)	58.8 (16.7)	<.001*
Sex (% female)	56.5	53.3	51.9	.155
White (%)	31.2	39.0	29.8	.177
Black (%)	23.3	37.8	38.9	
Hispanic (%)	36.3	32.9	30.8	
Other (%)	1.5	3.3	2.1	
Insurance: commercial (%)	36.3	35.7	13.1	<.001
Insurance: CMS (%)	61.7	61.6	35.7	
Insurance: self-pay/other (%)	2.0	2.7	36.3	
Mortality (%)	1.8	1.8	1.5	<.001†
Mean CMI (STD)	1.93 (1.41)	1.93 (1.07)	2.06 (1.36)	<.001‡
DD: home (%)	87.8	86.5	63.7	<.001
DD: nonhome (%)	10.7	11.4	33.8	
Indexed HLOS [95% CI]	0.605 [0.602–0.608]	0.624 [0.621–0.628]	1.00	<.001
Indexed hospital charges [95% CI]	0.777 [0.775–0.7780]	0.805 [0.803–0.807]	1.00	<.001

Zones A and B used AHU HEPA/AAPT remediation and mixed AHU-HEPA/AAPT return, respectively. Zone C featured AHU-HEPA filtration only.
DD, discharge destination.
* Unadjusted mortality without consideration of patient age and CMI differences. Subsequent adjustment shows that likelihood of mortality is similar for all 3 study groups.
† Due to differences in CMI; final results are adjusted for this variable.
‡ Age was included in original CMI calculations and thus no additional adjustments specific to patient age were made.

Table V
Key environmental metrics associated with environmental purity, as previously published by the same research team[17]

Parameter	Zone A	Zone B	Zone C
Viable fungi by air (CFU/m^3)	0	7	144
Viable fungi by swab (CFU/in^2)	0	50	25
Viable bacteria by air (CFU/m^3)	0	35	141
Viable bacteria by swab (CFU/in^2)	25	0	425
Volatile organic compounds (ppb)	1,300	2,350	3,100

As the level of environmental purity increased the airborne and surface bacterial, airborne fungal, and VOC level decreased. Data used with permission.
CFU, colony forming unit; *ppb*, parts per billion.

A (comprehensive AAPT remediation) continued to improve over time as the purified air was recirculated through the space. Zone C served as the control zone with AHU HEPA remediation and did not experience any improvement in pathogen levels throughout the study, confirming that the decreased pathogen levels were due to the installation of the AAPT versus another outside factor.

We hypothesized that the environmental benefits of the AAPT would include improved clinical and economic metrics. In this study, an association was noted between the deployment of AAPT (zones A and B) and observed decreases in normalized, CMI-adjusted utilization of hospital resources. More specifically, statistically significant improvements were found in normalized HLOS, discharge to home, and associated decreases in HC. Within the broader context of environmental purity and air filtration, the endpoints of clinical and resource consumption highlight a new and previously poorly explored relationship.[38] This finding may be especially important in clinical settings that require high environmental purity standards, such as the operating room and intensive care spaces.[39–41]

Figure 4 superimposes previously published environmental data on airborne pathogen levels for each study zone[17] compared with the present study outcomes in the corresponding patient units. There appears to be a correlation between the level of environmental purity and outcomes by zone. As the environmental purity increased, the HLOS and HC decreased. A cost and benefit analysis was conducted and the installation of the AAPT resulted in 23% less costs in Zone A compared with zone C. Although the present study was not powered to demonstrate differences in HAIs across the 3 air purification areas, we did note a trend toward fewer reported HAIs in the AAPT zones (0.40% and 0.48%) when compared to the control zone (0.63%). Given the already very low incidence of HAIs at the institution, a much larger sample of patients (and much longer study duration) would be required to demonstrate statistically significant differences.

HLOS is a complex metric that institutions are constantly striving to improve.[42] As hospitals reach capacity, they are forced to either divert patients to other facilities or hold patients in the emergency department until a hospital bed becomes available.[43,44] This practice can put a strain on resource allocation, patient satisfaction, and consequently hospital reputation.[42–44] With a decrease in HLOS, hospitals are able to optimize patient throughput and clinical space capacity while utilizing resources and facilities that are already in place.[45,46]

SUBIs are caused by potentially harmful pathogens present in the clinical space.[6] These infections are not currently tracked or reported unless a positive culture is identified or an outbreak occurs. Many such outbreaks have occurred in the past few years alone, including invasive fungal and multidrug-resistant bacterial infections.[7–9] Subclinical infections cannot be ignored and likely contribute to increased HLOS in the hospital setting. The AAPT-mediated removal of these harmful pathogens may play a role in decreasing HLOS and thus increasing hospital capacity and throughput. Better understanding of the airborne propagation of infectious surface fomites from the air to clinical surfaces and throughout the clinical space based on air flow patterns is critical in the effort to remediate these harmful pathogens.[17] Based on the current experience, management of airborne illnesses and nosocomial infections should incorporate methodology that considers the patient as well as surface and air disinfection.[47–49] Additional research is warranted in this important area.

This study has several important limitations. First, it is a retrospective evaluation with biases inherent to such study designs. Second, the final comparison subset groups are derived from a much larger, primary cohort of patients. The process of elimination of certain patient subgroups (eg, bariatric surgery patients) to attain more balanced comparison samples between the 3 study zones may have introduced additional biases. Third, the CMI-based adjustment for patient acuity has important limitations in that it does not always

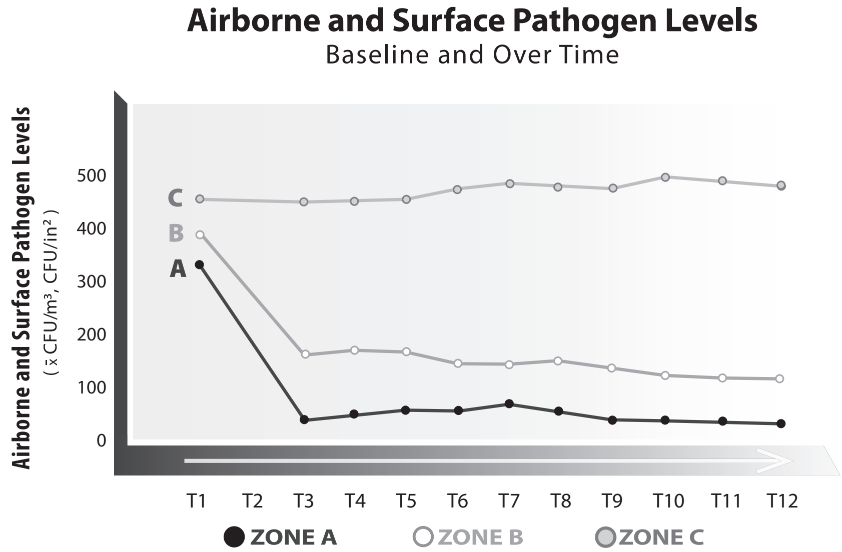

Fig 3. Airborne and surface pathogen levels over time. Data from the previously published environmental study.[17] Reproduced with permission.

account for important acute physiologic and nonphysiologic parameters. Fourth, the research team utilized administrative data that were not originally intended for measuring clinical outcome parameters. Finally, the present study was not powered to detect differences in HAI, mortality, or readmission. More specifically, the HAI incidence is very low, and thus, data are very limited, lack granularity, and do not allow for meaningful analyses beyond descriptive statements of findings. Furthermore, when specifically discussing surgical site infections, there is no strictly defined protocol for the management of these occurrences at the study hospital. The care of these wounds is therefore, directed by the primary surgeon or team, and there was lack of standardization across how different types of wounds are managed. Consequently, it was not possible to account for the impact of wound care on study-specific outcomes. Still, a trend toward fewer infections in AAPT areas represents a strong case for further research in this important area.

In conclusion, patients in the AAPT clinical zones demonstrated statistically significant improvements in health care resource utilization after adjusting for CMI. More specifically, the research team noted marked improvements in HLOS, discharge to home, and an associated decrease in HC. Overall, the findings support the hypothesis that environmental factors may favorably impact clinical and economic outcomes. In addition, a decreasing HAI trend was noted for areas serviced with AAPT.

Conflict of interest/Disclosure

Stanislaw P. Stawicki is an employee of St. Luke's University Hospital Network (SLUHN) and served as the Principal Investigator for this study (see grant funding details under Funding/Support). Samantha Wolfe is an employee of SLUHN and does not have any disclosures. Chad Brisendine is an employee of SLUHN and does not

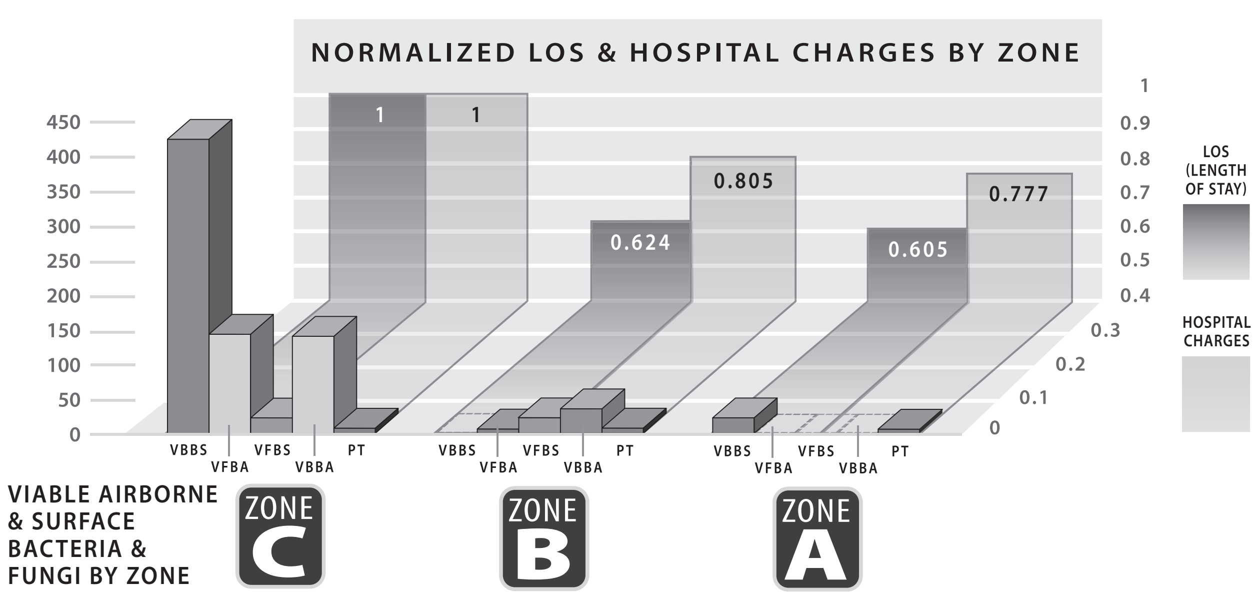

Fig 4. The clinical and economic outcomes mirrored the level of environmental purity from zone C to zone B to zone A. Data from the previously published environmental study.[17] Reproduced with permission. *PT*, particulates; *VBBA*, viable bacteria by air; *VBBS*, viable bacteria by swab; *VFBA*, viable fungi by air; *VFBS*, viable fungi by swab.

have any disclosures. Sherrine Eid is a third-party epidemiologist working as a consultant for LifeAire Systems (LAS). Matthew Zangari is an employee of SLUHN and does not have any disclosures. Frank Ford is an employee of SLUHN and does not have any disclosures. Beverly Snyder was an employee of SLUHN at the start of the study, has since retired, and does not have any disclosures. William Moyer is an employee of SLUHN and does not have any disclosures. Lee Levicoff is an employee of SLUHN and does not have any disclosures. William R. Burfeind is an employee of SLUHN and does not have any disclosures.

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