Ventilator-Associated Pneumonia Surveillance and Benchmarking in a Standardized Saudi Healthcare-Associated Infection Dataset: A Retrospective Unit-Month Evaluation

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Abstract

Background: Healthcare-associated infections (HAIs) are preventable threats to patient safety, and ventilator-associated pneumonia (VAP) is a priority device-associated outcome for intensive care infection prevention.

Methods: We conducted a retrospective multicenter surveillance evaluation using standardized Saudi HAI patient-level, microbiology, and unit-month denominator files from January 2023 through December 2025. The primary outcome was VAP. Rates were calculated per 1,000 ventilator-days, and adult ICU comparisons were estimated with Poisson regression using log ventilator-days as the offset.

Results: The dataset included 5,000 admissions, 686 unit-months, 33,356 patient-days, and 3,817 ventilator-days. Eighty-seven HAIs were recorded, including 30 VAP events. The overall VAP rate was 7.86 per 1,000 ventilator-days (95% CI, 5.30-11.22). VAP occurred only in adult ICUs, with higher crude rates in the medical ICU than in the surgical ICU. The post-intervention period had a lower crude rate than the pre-intervention period, but adjusted Poisson models did not show statistically significant differences by ICU type or intervention period.

Conclusions: VAP surveillance in this dataset identifies adult ICUs, especially the medical ICU, as the most relevant target for focused infection prevention review. Findings support continued device-denominator surveillance, VAP bundle auditing, microbiology monitoring, and cautious interpretation of pre/post trends.

Keywords: healthcare-associated infection; ventilator-associated pneumonia; infection prevention and control; surveillance; Poisson regression; Saudi Arabia

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Introduction

HAI Burden and Patient-Safety Relevance

Healthcare-associated infections (HAIs) remain a major patient-safety problem because they affect vulnerable hospitalized populations, prolong admission, increase antimicrobial exposure, and consume infection prevention and clinical resources. Contemporary incidence work shows that HAIs are not distributed uniformly across hospitals or clinical services; instead, risk concentrates in settings with invasive devices, complex surgery, older patients, and high acuity (Stewart et al., 2021). HAIs also intersect with antimicrobial resistance, a global threat responsible for substantial mortality and disability, particularly when infections involve pathogens such as Staphylococcus aureus, Klebsiella pneumoniae, Acinetobacter baumannii, Pseudomonas aeruginosa, and Escherichia coli (Antimicrobial Resistance Collaborators, 2022). For infection prevention and control (IPC) programs, therefore, HAI surveillance is not simply a reporting exercise; it is a mechanism for identifying preventable harm, prioritizing limited resources, and evaluating whether prevention practices are reaching the patients at greatest risk.

Infection Types Represented in the Dataset

The standardized Saudi HAI dataset includes several outcome types representing common healthcare epidemiology priorities: ventilator-associated pneumonia (VAP), central line-associated bloodstream infection (CLABSI), catheter-associated urinary tract infection (CAUTI), and surgical site infection (SSI). Each outcome has a distinct exposure pathway and prevention logic. CLABSI is linked to central venous catheter insertion and maintenance practices, CAUTI to urinary catheter necessity and duration, SSI to procedure-related and perioperative factors, and

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VAP to invasive mechanical ventilation. Among these outcomes, VAP is especially appropriate for primary analysis because it is device-associated and can be expressed using ventilator-days as the exposure denominator. VAP is among the most frequent ICU-acquired infections, with reported incidence varying widely by setting and diagnostic criteria; it is associated with longer mechanical ventilation and ICU stay, and prevention depends heavily on reducing ventilator exposure and reliably implementing evidence-based respiratory-care practices (Papazian et al., 2020). Recent expert guidance emphasizes practical VAP prevention strategies, including minimizing intubation and ventilation duration, using sedation minimization strategies, and embedding performance measures within hospital IPC programs (Klompas et al., 2022).

Surveillance, Rate-Based Monitoring, and Benchmarking

Valid surveillance requires more than counting infections. Crude counts are strongly influenced by patient volume, device use, surgical volume, and case mix; consequently, IPC decisions should be based on rates, stratified comparisons, and, where possible, risk-adjusted benchmarking. Device-associated outcomes should be reported with device-day denominators, such as VAP per 1,000 ventilator-days, CLABSI per 1,000 central-line days, and CAUTI per 1,000 urinary catheter-days, whereas SSI should use eligible procedure counts. This denominator-based approach permits fairer comparison across units and time periods, supports detection of unusual increases, and allows prevention efforts to be targeted to the clinical areas where excess risk is most plausible. National surveillance analyses have also demonstrated the value of standardized infection ratios and predicted-event methods for comparing observed infections with expected infections while accounting for baseline risk and reporting differences (Weiner-Lastinger et al., 2022). Similarly, recent SHEA/IDSA/APIC guidance for CLABSI, CAUTI, and SSI prevention emphasizes that surveillance metrics should be paired with

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implementation measures, adherence auditing, and feedback to clinical teams (Buetti et al., 2022; Calderwood et al., 2023; Patel et al., 2023).

Study Objectives

Primary Objective

The primary objective of this study is to evaluate VAP incidence in the Saudi HAI surveillance dataset by calculating VAP rates per 1,000 ventilator-days and comparing rates by unit, hospital or region, calendar time, and intervention period.

Secondary Objective

A secondary objective is to assess whether unit-level prevention indicators, including VAP bundle and hand hygiene compliance, are associated with differences in VAP rates after accounting for ventilator exposure. Additional descriptive analyses will summarize CLABSI, CAUTI, SSI, and microbiology findings to contextualize broader IPC priorities and support recommendations for targeted surveillance, prevention-bundle reinforcement, and ongoing benchmarking.

Methods

Study design and setting

This study was designed as a retrospective, multicenter healthcare-associated infection surveillance evaluation with a pre/post intervention component. The setting was a standardized Saudi HAI surveillance dataset representing four hospitals or regions (Riyadh, Jeddah, Dammam, and Madinah) and five inpatient unit categories: medical ICU, surgical ICU, neonatal ICU, medical ward, and surgical ward. The surveillance period was defined by admission month and denominator month from January 2023 through December 2025. Because some late-2025 admissions had infection or discharge dates extending into January 2026, these dates were

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retained when they were linked to admissions in the surveillance dataset; however, the denominator period for rate calculation ended in December 2025. The assigned intervention indicator classified January 2023 through June 2024 as the pre-intervention period and July 2024 through December 2025 as the post-intervention period.

Population and unit of analysis

The patient-level file included 5,000 admission records with demographic characteristics, unit assignment, device exposure, comorbidities, HAI status, and selected outcomes. The denominator file included 686 hospital-unit-month records containing patient-days, device-days, procedure counts, HAI counts, and process-compliance measures. The microbiology file included culture records linked to admissions by AdmissionID. All admission-level records were included for descriptive characterization of the surveillance population and overall HAI distribution. The primary analytic unit for VAP incidence was the hospital-unit-month, because device-associated rates require an infection count and an exposure denominator measured over the same surveillance stratum. For the primary VAP rate model, records were restricted to unit-months with at least one ventilator-day; models focused on medical and surgical ICUs because all VAP events occurred in ICU settings and those units represented the clinically relevant ventilated adult population. Unit-months with zero ventilator-days were retained for descriptive denominator accounting but excluded from models requiring a log ventilator-day offset.

Case definitions and outcomes

The primary outcome was ventilator-associated pneumonia, operationalized as a VAP event recorded in the denominator file and as HAI_Type = VAP in the patient-level file. VAP was selected because it is a device-associated pneumonia outcome among mechanically ventilated patients and is appropriately expressed using ventilator-days as the exposure denominator

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(Papazian et al., 2020). The dataset also included CLABSI, CAUTI, and SSI, which were analyzed descriptively to contextualize broader IPC priorities. CLABSI and CAUTI were treated as device-associated infections linked to central-line days and urinary catheter-days, respectively; SSI was treated as a procedure-associated outcome linked to eligible procedures. Because infections were already labeled in the dataset, the analysis used the provided operational labels rather than re-adjudicating cases from raw clinical signs, radiology, microbiology, or procedure notes. This approach supports reproducibility but introduces potential misclassification if local case ascertainment differed from standardized surveillance definitions. Contemporary VAP prevention and surveillance guidance emphasizes that outcome monitoring should be interpreted alongside ventilator exposure and process measures rather than as crude counts alone (Klompas et al., 2022).

Denominators and exposure time

Patient-days were defined as the monthly sum of inpatient days within each hospital-unit stratum. Ventilator-days were defined as the monthly sum of days on invasive mechanical ventilation and served as the primary exposure denominator for VAP. Central-line days, urinary catheter-days, and SSI-eligible procedure counts were used as denominators for CLABSI, CAUTI, and SSI descriptive rates, respectively. VAP incidence was calculated as the number of VAP events divided by ventilator-days and multiplied by 1,000. CLABSI and CAUTI rates were calculated per 1,000 relevant device-days, and SSI rates were calculated per 100 eligible procedures. Device utilization was calculated as device-days divided by patient-days for unit-month strata when used to describe exposure intensity.

Variable and risk factors

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Stratification and adjustment variables were selected a priori based on epidemiologic plausibility and dataset availability. Core unit-month variables included unit type, hospital/region, year, month, intervention period, patient-days, ventilator-days, VAP bundle compliance, and hand hygiene compliance. Patient-level variables used for descriptive summaries included age group, sex, nationality, BMI, diabetes, chronic kidney disease, immunosuppression, APACHE II score, mechanical ventilation status, ventilator-days, ICU onset, 30-day mortality, and HAI mortality. Microbiology variables included organism, specimen type, multidrug-resistant status, ESBL status, carbapenem resistance, and contaminant flag. Denominator and process-compliance variables were complete. Patient-level BMI was missing for 281 admissions (5.6%), while APACHE II and ASA score were structurally concentrated in ICU and surgical records; therefore, these variables were summarized only among eligible or nonmissing records and were not used as mandatory covariates in the primary unit-month VAP model. Microbiology records flagged as contaminants were excluded from organism summaries.

Statistical analysis

Descriptive epidemiology summarized person, place, and time patterns using counts, percentages, medians, and interquartile ranges as appropriate. HAI frequencies were tabulated overall and by type, unit, hospital/region, period, and year. Monthly VAP rates were plotted to evaluate time trends and potential unusual increases, and unit-specific rates were compared using bar or dot plots with denominator definitions shown in figure notes. Exact or Poisson confidence intervals were calculated for incidence rates where appropriate. The primary benchmarking analysis estimated VAP incidence rate ratios using Poisson regression with the VAP count as the dependent variable and the natural logarithm of ventilator-days as an offset. Candidate predictors included unit type, intervention period, hospital/region, calendar time, VAP bundle compliance,

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and hand hygiene compliance. Poisson modeling was selected because the outcome was a count of relatively rare surveillance events occurring over a known exposure denominator. Overdispersion was assessed using the Pearson chi-square statistic divided by residual degrees of freedom; if substantial overdispersion was detected, a negative binomial model or robust standard errors was planned. Multicollinearity among process measures was evaluated using correlation matrices and variance inflation factors before including them in the same adjusted model. A secondary patient-level logistic regression describing factors associated with VAP was considered exploratory only because the primary surveillance question concerned rates per ventilator-days, not individual binary risk alone. All analyses were conducted using annotated R code, and the submitted reproducibility package includes the analysis script, codebook, derived-variable definitions, and a data-cleaning note documenting exclusions, linkage decisions, missingness, and denominator construction.

Results

Study sample and denominators

The patient-level file contained 5,000 admissions from four hospital or regional strata: Riyadh, Jeddah, Dammam, and Madinah. Admissions were distributed across medical wards (n = 1,652), surgical wards (n = 1,416), medical ICUs (n = 858), surgical ICUs (n = 793), and neonatal ICUs (n = 281). The analytic denominator file contained 686 hospital unit-month observations spanning January 2023 through December 2025. Across all unit-months, the dataset contributed 33,356 patient-days, 3,817 ventilator-days, 6,176 central-line days, 6,521 urinary-catheter days, and 1,719 SSI-eligible procedures (Table 1). The patient cohort had a mean age of 49.3 years; 2,784 admissions (55.7%) were male. The median length of stay was 6 days (interquartile range, 4-9 days). Invasive-device exposure was common in the ICU population and included 1,053

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mechanically ventilated admissions, 1,713 admissions with a central line, and 2,054 admissions with a urinary catheter.

Table 1. Study sample, unit-month denominators, device exposure, and HAI events by unit.

Unit	Admissions	Unit-months	Patient-days	Ventilator-days	CL/UC days	SSI-eligible procedures	All HAI / VAP
ICU_Medical	858	144	7,679	1,832	2,629 / 2,708	145	34 / 18
ICU_Surgical	793	139	7,073	1,774	2,470 / 2,617	493	37 / 12
NICU	281	116	3,227	59	566 / 269	32	1 / 0
Ward_Med	1,652	143	8,285	90	275 / 502	177	2 / 0
Ward_Surg	1,416	144	7,092	62	236 / 425	872	13 / 0
Total	5,000	686	33,356	3,817	6,176 / 6,521	1,719	87 / 30

Note. CL = central-line days; UC = urinary-catheter days; SSI = surgical site infection; HAI = healthcare-associated infection; VAP = ventilator-associated pneumonia.

Overall, 87 admissions had a recorded HAI, corresponding to 1.7% of admissions. SSI was the most frequently labeled infection type (33 events), followed by VAP (30 events), CAUTI (16 events), and CLABSI (8 events). VAP events were concentrated in adult ICUs: 18 events occurred in the medical ICU and 12 in the surgical ICU; no VAP events were recorded in the neonatal ICU, medical ward, or surgical ward. Among the 30 VAP admissions, the mean age was 52.2 years, 19 (63.3%) were male, and the median length of stay was 9 days. The mean APACHE II score among VAP admissions was 20.6, and 3 of the 30 VAP admissions had 30-day mortality recorded. Microbiology records were available for all 30 VAP admissions and all VAP cultures were from bronchoalveolar lavage specimens. The organisms identified among VAP cases were Acinetobacter baumannii (8/30, 26.7%), Klebsiella pneumoniae (7/30, 23.3%), Escherichia coli (6/30, 20.0%), methicillin-resistant Staphylococcus aureus (6/30, 20.0%), and Pseudomonas aeruginosa (3/30, 10.0%).

Incidence and rates

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The overall VAP rate was 7.86 infections per 1,000 ventilator-days (95% CI, 5.30-11.22) across the full surveillance period (Table 2). The medical ICU had 18 VAP events during 1,832 ventilator-days, yielding a rate of 9.83 per 1,000 ventilator-days (95% CI, 5.82-15.53). The surgical ICU had 12 VAP events during 1,774 ventilator-days, yielding a rate of 6.76 per 1,000 ventilator-days (95% CI, 3.50-11.82). The remaining unit categories contributed relatively few ventilator-days and had zero observed VAP events; their zero-event estimates are therefore shown with wide upper confidence bounds in Table 2. By calendar year, the aggregate VAP rate was 8.89 per 1,000 ventilator-days in 2023, 8.09 per 1,000 ventilator-days in 2024, and 6.70 per 1,000 ventilator-days in 2025.

Table 2. VAP rates by unit and intervention period.

Group	VAP events	Ventilator-days	Rate per 1,000 ventilator-days (95% CI)
Overall	30	3,817	7.86 (5.30-11.22)
ICU_Medical	18	1,832	9.83 (5.82-15.53)
ICU_Surgical	12	1,774	6.76 (3.50-11.82)
NICU	0	59	0.00 (0.00-62.52)
Ward_Med	0	90	0.00 (0.00-40.99)
Ward_Surg	0	62	0.00 (0.00-59.50)
Pre-intervention	17	1,926	8.83 (5.14-14.13)
Post-intervention	13	1,891	6.87 (3.66-11.76)
Adult ICU pre-intervention	17	1,838	9.25 (5.39-14.81)
Adult ICU post-intervention	13	1,768	7.35 (3.92-12.57)

Note. Rates are VAP events per 1,000 ventilator-days. Confidence intervals are exact Poisson intervals. Adult ICU rows include medical ICU and surgical ICU only.

When stratified by intervention period, 17 VAP events occurred during 1,926 ventilator-days before the intervention, for a crude rate of 8.83 per 1,000 ventilator-days (95% CI, 5.14-14.13). During the post-intervention period, 13 VAP events occurred during 1,891 ventilator-days, for a

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crude rate of 6.87 per 1,000 ventilator-days (95% CI, 3.66-11.76). Restricting the comparison to adult ICU unit-months produced similar estimates: 9.25 per 1,000 ventilator-days before the intervention and 7.35 per 1,000 ventilator-days after the intervention. Within adult ICUs, the intervention-period pattern differed by unit. The medical ICU rate increased from 8.59 per 1,000 ventilator-days pre-intervention to 11.10 per 1,000 ventilator-days post-intervention, whereas the surgical ICU rate decreased from 9.92 to 3.46 per 1,000 ventilator-days.

Time-based findings

Monthly aggregate VAP counts ranged from 0 to 3 events, and monthly VAP rates ranged from 0 to 27.52 per 1,000 ventilator-days (Figure 1). The highest aggregate monthly rates occurred in November 2023 (3 events; 27.52 per 1,000 ventilator-days) and April 2025 (3 events; 24.79 per 1,000 ventilator-days). Using the prespecified signal criterion of an observed monthly VAP count exceeding the one-sided 95% Poisson prediction limit based on the overall VAP rate and that month's ventilator-days, no aggregate month met the threshold for a surveillance signal. In unit-specific adult ICU screening, two unit-months met the same signal rule: surgical ICU in June 2024 and medical ICU in April 2025. These unit-months are presented descriptively as surveillance signals rather than confirmed outbreaks because organism relatedness and transmission data were not available in the analytic files.

Figure 1. Monthly VAP rate per 1,000 ventilator-days, January 2023-December 2025.

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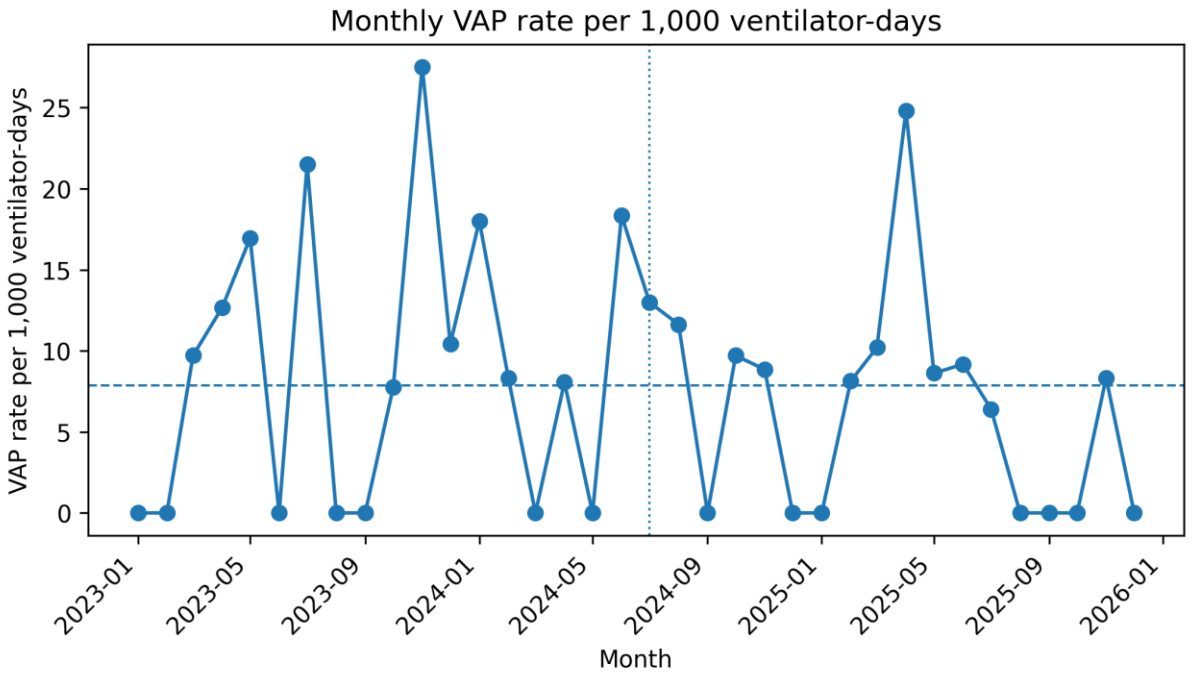


Note. Dashed horizontal line indicates the overall VAP rate; dotted vertical line indicates the start of the post-intervention period in July 2024.

Risk-adjusted and benchmarking findings

Adult ICU unit-months were used for the primary VAP rate model because all VAP events occurred in the medical or surgical ICU and these units contributed nearly all ventilator-days. In the hospital-adjusted Poisson model with log ventilator-days as the offset, the medical ICU had a higher adjusted VAP rate than the surgical ICU, but the confidence interval included the null (adjusted rate ratio [aRR], 1.43; 95% CI, 0.71-2.90; p = .320) (Table 3). The post-intervention period had a lower adjusted VAP rate than the pre-intervention period, but this estimate was also imprecise (aRR, 0.79; 95% CI, 0.38-1.62; p = .522). Hospital-level fixed-effect estimates were not statistically distinguishable from the reference hospital in this model. The Pearson chi-square/df for the primary Poisson model was 1.17, indicating no meaningful overdispersion requiring a negative binomial primary model. In a secondary process model that added VAP

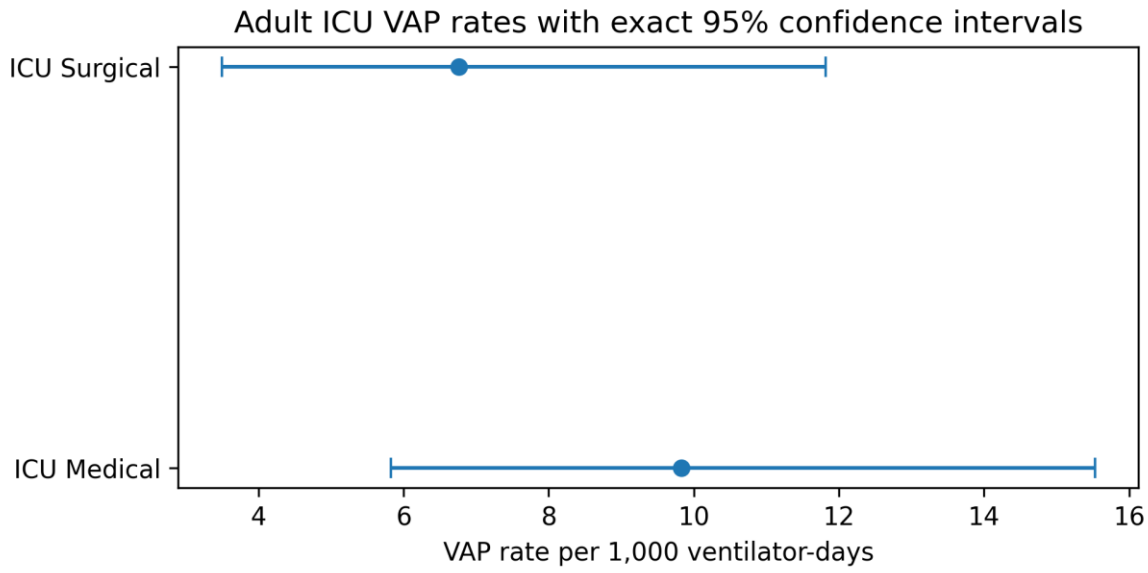
bundle compliance, each 10 percentage-point higher bundle-compliance value was associated with an aRR of 0.84 (95% CI, 0.51-1.37; p = .486).

Table 3. Adjusted VAP rate ratios from Poisson regression models among adult ICU unit-months.

Model	Predictor	Reference	aRR	95% CI	p
Primary model	Medical ICU	Surgical ICU	1.43	0.71-2.90	.320
Primary model	Post-intervention	Pre-intervention	0.79	0.38-1.62	.522
Secondary process model	VAP bundle compliance, per 10 percentage-point higher value	Continuous	0.84	0.51-1.37	.486

Note. aRR = adjusted rate ratio. Primary model included adult ICU unit-months and adjusted for hospital with log ventilator-days as the offset. The secondary process model added VAP bundle compliance. Robust standard errors were used. Pearson chi-square/df for the primary model was 1.17.

Figure 2. Adult ICU VAP rate comparison with exact 95% confidence intervals.



Note. Rates are VAP events per 1,000 ventilator-days. Exact Poisson confidence intervals are shown.

Figure 2 displays the adult ICU unit comparison with exact confidence intervals. The medical ICU point estimate was higher than the surgical ICU point estimate, but the intervals overlapped. Across crude and adjusted analyses, the results show a VAP burden concentrated in

mechanically ventilated adult ICU patients, with lower post-intervention point estimates overall but limited precision due to the small number of VAP events.

Discussion

Principal Findings

This retrospective unit-month surveillance evaluation identified VAP as the most analytically coherent HAI outcome in the standardized Saudi dataset because every event was linked to a clear device denominator and occurred in clinically appropriate adult ICU settings. Across 3,817 ventilator-days, the overall VAP rate was 7.86 per 1,000 ventilator-days, with higher crude incidence in the medical ICU than in the surgical ICU and a lower crude rate after the intervention than before it. However, adjusted Poisson models showed wide confidence intervals and did not demonstrate statistically significant independent differences by ICU type, intervention period, or VAP bundle compliance. Microbiology results showed a predominance of gram-negative respiratory pathogens, especially Acinetobacter baumannii and Klebsiella pneumoniae, with more than one-third of VAP isolates classified as multidrug resistant.

Epidemiologic Interpretation

The concentration of VAP events in the medical and surgical ICUs is epidemiologically consistent with the exposure pathway for ventilator-associated pneumonia: mechanical ventilation, critical illness, impaired airway protection, and frequent invasive care. The higher crude rate in the medical ICU may reflect differences in case mix, ventilator duration, severity of illness, sedation practices, respiratory comorbidity, or underlying antimicrobial pressure rather than unit performance alone. This distinction is important because crude rates compare observed events per device-days but do not fully account for patient acuity or hospital-level differences. After adjustment for hospital and intervention period, the medical ICU rate ratio remained above

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1.0 but was imprecise, indicating that the dataset supports targeted review rather than a definitive conclusion that one ICU had excess preventable risk.

The post-intervention decrease from 8.83 to 6.87 VAP events per 1,000 ventilator-days was directionally favorable, but the adjusted post-intervention rate ratio was not statistically significant. This pattern suggests that the intervention signal should be interpreted as a surveillance finding requiring continued monitoring, not proof of effectiveness. Monthly rates were variable because VAP events were sparse and monthly ventilator-day denominators were modest; therefore, isolated peaks can occur from only two or three cases. The time-series pattern did not show a sustained multimonth cluster, so the findings are more compatible with endemic device-associated risk and episodic high-rate months than with a clear outbreak.

Organism patterns also have IPC relevance. A. baumannii, K. pneumoniae, E. coli, MRSA, and P. aeruginosa are plausible VAP pathogens and are frequently associated with ICU antimicrobial exposure, ventilator care, environmental persistence, and cross-transmission risk. The 36.7% MDR proportion in VAP cultures strengthens the rationale for linking VAP prevention with antimicrobial stewardship, respiratory equipment reprocessing, hand hygiene, environmental cleaning, and unit-level feedback. Recent reviews emphasize that VAP remains difficult to diagnose consistently and that both host factors and care processes influence observed rates (Papazian et al., 2020). The antimicrobial resistance burden associated with bacterial infections further supports prevention as an IPC and stewardship priority (Antimicrobial Resistance Collaborators, 2022).

Comparison With Recent Literature

The overall VAP rate in this dataset falls within the broad range described in contemporary ICU literature, although direct comparison is limited by differences in surveillance definitions,

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diagnostic intensity, patient acuity, and denominator construction. Recent prevention guidance emphasizes avoiding intubation when possible, minimizing ventilator duration, elevating the head of the bed, daily assessment for extubation readiness, oral care, subglottic secretion management when appropriate, and multidisciplinary audit-and-feedback processes (Klompas et al., 2022). Compared with large surveillance reports, this dataset is smaller and more vulnerable to statistical instability, but its rate-based findings align with the general principle that device-associated infection prevention should be monitored by exposure-adjusted rates rather than counts alone. The COVID-19 era NHSN analysis also illustrates how device-associated infection rates can shift when ICU strain, staffing, device utilization, and patient severity change, reinforcing the need to interpret trends in context rather than assuming that crude changes represent intervention effects (Weiner-Lastinger et al., 2022).

Implications for Infection Prevention Practice

The first priority should be adult ICU-focused VAP prevention rather than hospital-wide undifferentiated HAI messaging. Medical ICU and surgical ICU teams should receive monthly VAP rate feedback per 1,000 ventilator-days, paired with ventilator utilization and bundle-compliance dashboards. Second, the medical ICU should receive focused review of ventilator necessity, sedation interruption, spontaneous breathing trial documentation, oral-care reliability, head-of-bed elevation, and respiratory equipment handling. Third, months with two or more VAP events or rates clearly above the surveillance mean should trigger rapid case review to identify common organisms, shared locations, staffing patterns, equipment issues, or lapses in bundle elements. Fourth, because MDR organisms were common, VAP prevention should be integrated with antimicrobial stewardship, empiric therapy review, de-escalation practices, and microbiology surveillance. Finally, the surveillance system should continue to preserve patient-

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days, ventilator-days, unit-month identifiers, and bundle-compliance fields so that IPC teams can distinguish changes in infection risk from changes in exposure.

Strengths and Limitations

Strengths of this evaluation include a multicenter structure, linked patient-level and unit-month denominator files, use of ventilator-days as the primary exposure denominator, microbiology linkage, and a prespecified rate-modeling approach aligned with device-associated surveillance principles. The analysis also reports exact Poisson confidence intervals and explicitly separates crude from adjusted comparisons. Limitations should temper interpretation. The dataset provides operationally labeled HAI outcomes but not the full clinical, radiographic, or microbiologic criteria needed to independently validate VAP according to surveillance definitions, creating potential misclassification. Patient-level severity measures were incomplete outside ICU settings, and the small number of VAP events limited multivariable adjustment. The pre/post comparison was observational and may be confounded by secular trends, staffing, patient mix, or changes in diagnostic practice. Bundle-compliance variables were aggregated and may not capture bedside adherence for the specific patients who developed VAP. Finally, because the analysis used a standardized assigned dataset, generalizability to all Saudi hospitals or to other health systems should not be assumed.

Conclusion

In this standardized Saudi HAI dataset, VAP was an appropriate primary surveillance outcome because it combined a clinically meaningful event definition with a valid device denominator and actionable ICU prevention implications. The findings support continued adult ICU VAP surveillance, monthly rate feedback, focused review of high-rate months, and reinforced

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ventilator-care prevention practices, while recognizing that adjusted models did not confirm statistically significant unit or intervention effects.

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Appendices

Appendix A. Annotated R Code

The following script reproduces the study denominators, VAP rate tables, exact Poisson confidence intervals, time-based and unit-comparison figures, Poisson rate models, diagnostics, and microbiology summaries from the three supplied CSV files. It is included as a reproducibility appendix and can also be saved as an .R script.

```
# Annotated R reproducibility script for the VAP surveillance manuscript
# Purpose: Reproduce descriptive tables, VAP rate calculations, figures, and Poisson models.
# Inputs: The three CSV files supplied with the assignment, placed in the working directory.

# ---- 1. Packages ----
# Install packages if needed: install.packages(c("readr", "dplyr", "ggplot2", "MASS"))
library(readr)
library(dplyr)
library(ggplot2)
library(MASS)

# ---- 2. Import data ----
input_dir <- "."
patients <- read_csv(file.path(input_dir, "SAUDI_HAI_PATIENT_DATA_5000 (1).csv"), show_col_types
= FALSE)
micro <- read_csv(file.path(input_dir, "SAUDI_HAI_MICRO_DATA (1).csv"), show_col_types = FALSE)
denom <- read_csv(file.path(input_dir, "SAUDI_HAI_DENOMINATORS_UNIT_MONTH (1).csv"),
show_col_types = FALSE)

# ---- 3. Derived variables ----
denom <- denom %>%
  mutate(
    Date = as.Date(sprintf("%04d-%02d-01", Year, Month)),
    Period = if_else(PostIntervention == 1, "Post-intervention", "Pre-intervention"),
    AdultICU = UnitID %in% c("ICU_Medical", "ICU_Surgical"),
    VAP = if_else(is.na(VAP), 0, VAP)
  )

patients <- patients %>%
  mutate(
    VAP_event = if_else(HAI_Type == "VAP", 1, 0),
    HAI_event = if_else(HAI_Any == 1, 1, 0)
  )

# Exact Poisson confidence intervals for rates per 1,000 ventilator-days.
rate_ci <- function(events, exposure, multiplier = 1000) {
  if (is.na(exposure) || exposure <= 0) {
    return(data.frame(rate = NA_real_, lower = NA_real_, upper = NA_real_))
  }
  pt <- poisson.test(events, T = exposure)
  data.frame(
    rate = as.numeric(events / exposure * multiplier),
    lower = as.numeric(pt$conf.int[1] * multiplier),
    upper = as.numeric(pt$conf.int[2] * multiplier)
  )
}

# ---- 4. Table 1: Unit-level denominators and events ----
admissions_by_unit <- patients %>% count(UnitID, name = "Admissions")
unit_denom <- denom %>%
  group_by(UnitID) %>%
  summarise(
    Unit_months = n(),
```

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    Patient_days = sum(PatientDays),
    Ventilator_days = sum(VentilatorDays),
    Central_line_days = sum(CentralLineDays),
    Urinary_catheter_days = sum(UrinaryCatheterDays),
    SSI_eligible_procedures = sum(SSI_ProceduresEligible),
    VAP_events = sum(VAP),
    CLABSI_events = sum(CLABSI),
    CAUTI_events = sum(CAUTI),
    SSI_events = sum(SSI),
    .groups = "drop"
  ) %>%
  left_join(admissions_by_unit, by = "UnitID") %>%
  mutate(All_HAI = VAP_events + CLABSI_events + CAUTI_events + SSI_events) %>%
  select(UnitID, Admissions, Unit_months, Patient_days, Ventilator_days,
         Central_line_days, Urinary_catheter_days, SSI_eligible_procedures,
         All_HAI, VAP_events)
write_csv(unit_denom, "table1_unit_denominators.csv")

# ---- 5. Table 2: VAP rates by unit and period ----
rate_row <- function(label, data) {
  events <- sum(data$VAP)
  vent_days <- sum(data$VentilatorDays)
  ci <- rate_ci(events, vent_days)
  tibble(
    Group = label,
    VAP_events = events,
    Ventilator_days = vent_days,
    Rate_per_1000_ventilator_days = ci$rate,
    Lower_95_CI = ci$lower,
    Upper_95_CI = ci$upper
  )
}

table2 <- bind_rows(
  rate_row("Overall", denom),
  bind_rows(lapply(split(denom, denom$UnitID), function(x) rate_row(unique(x$UnitID), x))),
  bind_rows(lapply(split(denom, denom$Period), function(x) rate_row(unique(x$Period), x))),
  rate_row("Adult ICU pre-intervention", denom %>% filter(AdultICU, PostIntervention == 0)),
  rate_row("Adult ICU post-intervention", denom %>% filter(AdultICU, PostIntervention == 1))
)
write_csv(table2, "table2_vap_rates.csv")

# ---- 6. Figures ----
monthly <- denom %>%
  group_by(Date) %>%
  summarise(VAP_events = sum(VAP), Ventilator_days = sum(VentilatorDays), .groups = "drop") %>%
  mutate(VAP_rate = VAP_events / Ventilator_days * 1000)

overall_rate <- sum(denom$VAP) / sum(denom$VentilatorDays) * 1000
intervention_date <- as.Date("2024-07-01")

fig1 <- ggplot(monthly, aes(x = Date, y = VAP_rate)) +
  geom_line() +
  geom_point() +
  geom_hline(yintercept = overall_rate, linetype = "dashed") +
  geom_vline(xintercept = intervention_date, linetype = "dotted") +
  labs(
    title = "Monthly VAP rate, January 2023-December 2025",
    x = "Month",
    y = "VAP events per 1,000 ventilator-days"
  ) +
  theme_minimal()
ggsave("figure1_monthly_vap_rate.png", fig1, width = 7, height = 4, dpi = 300)

adult_units <- denom %>%
  filter(UnitID %in% c("ICU_Medical", "ICU_Surgical")) %>%
  group_by(UnitID) %>%
  summarise(VAP_events = sum(VAP), Ventilator_days = sum(VentilatorDays), .groups = "drop")
ci_list <- lapply(seq_len(nrow(adult_units)), function(i) rate_ci(adult_units$VAP_events[i],
adult_units$Ventilator_days[i]))
ci_df <- bind_rows(ci_list)
```

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adult_units <- bind_cols(adult_units, ci_df)

fig2 <- ggplot(adult_units, aes(x = UnitID, y = rate)) +
  geom_point(size = 3) +
  geom_errorbar(aes(ymin = lower, ymax = upper), width = 0.15) +
  labs(
    title = "Adult ICU VAP rate comparison",
    x = "Unit",
    y = "VAP events per 1,000 ventilator-days"
  ) +
  theme_minimal()
ggsave("figure2_adult_icu_vap_comparison.png", fig2, width = 6, height = 4, dpi = 300)

# ---- 7. Risk-adjusted rate models ----
adult_model <- denom %>%
  filter(UnitID %in% c("ICU_Medical", "ICU_Surgical"), VentilatorDays > 0) %>%
  mutate(
    UnitID = relevel(factor(UnitID), ref = "ICU_Surgical"),
    HospitalID = factor(HospitalID),
    PostIntervention = factor(PostIntervention, levels = c(0, 1), labels = c("Pre", "Post")),
    Bundle_10 = VAP_Bundle_Compliance * 10
  )

fit_primary <- glm(
  VAP ~ UnitID + PostIntervention + HospitalID,
  family = poisson(link = "log"),
  offset = log(VentilatorDays),
  data = adult_model
)

fit_process <- glm(
  VAP ~ UnitID + PostIntervention + Bundle_10 + HospitalID,
  family = poisson(link = "log"),
  offset = log(VentilatorDays),
  data = adult_model
)

extract_rr <- function(model) {
  est <- coef(summary(model))
  ci <- confint.default(model)
  data.frame(
    term = rownames(est),
    aRR = exp(est[, "Estimate"]),
    lower_95_CI = exp(ci[, 1]),
    upper_95_CI = exp(ci[, 2]),
    p_value = est[, "Pr(>|z|)"],
    row.names = NULL
  )
}

table3_primary <- extract_rr(fit_primary)
table3_process <- extract_rr(fit_process)
write_csv(table3_primary, "table3_primary_poisson_rr.csv")
write_csv(table3_process, "table3_process_poisson_rr.csv")

# ---- 8. Diagnostics and sensitivity ----
pearson_dispersion <- sum(residuals(fit_primary, type = "pearson")^2) / df.residual(fit_primary)
deviance_ratio <- deviance(fit_primary) / df.residual(fit_primary)
print(summary(fit_primary))
print(summary(fit_process))
print(paste("Primary model Pearson dispersion:", round(pearson_dispersion, 3)))
print(paste("Primary model deviance/df:", round(deviance_ratio, 3)))

# Optional negative binomial sensitivity model. Use only if overdispersion is substantial.
fit_nb <- try(glm.nb(VAP ~ UnitID + PostIntervention + HospitalID + offset(log(VentilatorDays)),
data = adult_model), silent = TRUE)
print(fit_nb)

# ---- 9. Microbiology summary for VAP events ----
vap_ids <- patients %>% filter(HAI_Type == "VAP") %>% pull(AdmissionID)
vap_micro <- micro %>% filter(AdmissionID %in% vap_ids)
```

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vap_micro_summary <- vap_micro %>%
  count(Organism, sort = TRUE) %>%
  mutate(percent = n / sum(n) * 100)
write_csv(vap_micro_summary, "vap_microbiology_summary.csv")

resistance_summary <- vap_micro %>%
  summarise(
    VAP_cultures = n(),
    MDR_n = sum(MDR, na.rm = TRUE),
    MDR_percent = mean(MDR, na.rm = TRUE) * 100,
    ESBL_n = sum(ESBL, na.rm = TRUE),
    ESBL_percent = mean(ESBL, na.rm = TRUE) * 100,
    Carbapenem_resistant_n = sum(CarbapenemResistant, na.rm = TRUE),
    Carbapenem_resistant_percent = mean(CarbapenemResistant, na.rm = TRUE) * 100
  )
write_csv(resistance_summary, "vap_resistance_summary.csv")
```

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Appendix B. Codebook and Derived Variables

Variable or derived field	Source file	Definition or analytic use
AdmissionID	Patient and microbiology files	Unique admission identifier used to link HAI records to microbiology culture records.
HospitalID / Region	Patient and denominator files	Hospital or regional stratum used for descriptive summaries and adjustment.
UnitID	Patient and denominator files	Clinical unit; primary unit comparison used ICU_Medical and ICU_Surgical.
Year / Month / Date	Patient and denominator files	Calendar time fields; Date was derived as the first day of each year-month for trend plotting.
Period / PostIntervention	Patient and denominator files	Pre/post intervention indicator. PostIntervention = 1 was recoded as Post-intervention; 0 as Pre-intervention.
PatientDays	Denominator file	Monthly inpatient exposure denominator by hospital-unit stratum.
VentilatorDays	Denominator file	Monthly mechanical-ventilation exposure denominator; primary denominator for VAP rates and offset in rate models.
CentralLineDays / UrinaryCatheterDays	Denominator file	Device-day denominators used for descriptive context for CLABSI and CAUTI.
SSI_ProceduresEligible	Denominator file	Procedure denominator for SSI descriptive context.
VAP	Denominator file	Monthly count of ventilator-associated pneumonia events; primary outcome count.
HAI_Type / HAI_Any	Patient file	Patient-level HAI outcome labels used to describe HAI distribution and identify VAP admissions.
VAP_event	Derived from patient file	Binary indicator equal to 1 when HAI_Type = VAP and 0 otherwise.
AdultICU	Derived from denominator file	Indicator equal to 1 for ICU_Medical or ICU_Surgical; used to restrict primary VAP models.
VAP rate	Derived	VAP events divided by ventilator-days, multiplied by 1,000.
Bundle_10	Derived from VAP_Bundle_Compliance	VAP bundle compliance scaled so a one-unit increase equals a 10 percentage-point increase.
Organism / MDR / ESBL / CarbapenemResistant	Microbiology file	Culture organism and resistance markers summarized for VAP-linked cultures.

Appendix C. Data Cleaning and Missingness Note

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Data files were imported without changing the original records. Dates were parsed or derived for analysis only: admission, discharge, HAI, and culture dates were treated as calendar dates, and unit-month denominator rows were assigned the first day of the corresponding month for plotting.

The denominator file had 686 unit-month rows and no missing values in the analytic denominator or process fields used for VAP surveillance. Rows with zero ventilator-days were retained in descriptive summaries but were not eligible for rate modeling because log ventilator-days cannot be used as an offset when exposure is zero.

The primary Poisson model was restricted to adult ICU unit-months from ICU_Medical and ICU_Surgical because all VAP events occurred in these two units. This avoided unstable comparisons involving units with minimal ventilator exposure and no observed VAP events.

Patient-level HAI_Type and HAI_Date were missing for admissions without recorded HAI and were treated as structurally missing rather than data-quality errors. BMI was missing for 281 admissions; APACHE_II and ASA_Score were missing mainly outside the clinical contexts where they are expected to be collected. These variables were not imputed and were not included in the primary unit-month rate model.

Microbiology analyses were limited to cultures linked by AdmissionID to VAP admissions. All 30 VAP admissions had a corresponding microbiology row and BAL specimen type. Resistance markers were summarized as recorded, without adjudication of colonization versus infection.

No imputation was performed. Exact Poisson confidence intervals were used for VAP rates because event counts were small. Poisson model diagnostics included Pearson dispersion and deviance-to-degrees-of-freedom checks; negative binomial modeling was specified as a sensitivity option if substantial overdispersion was detected.

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Appendix D. Requirement Crosswalk

Requirement	Where addressed
Title page and abstract	Title page and Abstract at the beginning of the manuscript.
Introduction moving from broad HAI burden to study objectives	Introduction paragraphs 1-4.
Replicable Methods with design, setting, population, case definitions, denominators, variables, missingness, software, and analysis plan	Methods section and Appendices A-C.
Study sample and denominators	Results text and Table 1.
Incidence/rate calculations with correct units and confidence intervals	Results text and Table 2.
Risk adjustment/benchmarking results	Results text and Table 3.
Time-based figure	Figure 1 monthly VAP rate trend.
Unit comparison figure	Figure 2 adult ICU VAP rate comparison.
Discussion with interpretation, recent literature, practice implications, strengths/limitations, and conclusion	Discussion section.
Reproducibility package	Appendix A R code, Appendix B codebook, Appendix C cleaning and missingness note.

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