Has the use of a digital hand hygiene monitoring tool been associated with decreased prevalence of hospital acquired infections in Siem Reap Provincial Referral Hospital?

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Abstract

Has the use of a digital hand hygiene monitoring tool been associated with a decreased prevalence of hospital acquired infections in Siem Reap Provincial Referral Hospital?

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The practice of hand hygiene (HH) is a key intervention to decrease the rate of healthcare associated infections (HCAI). We performed a pre-post analysis to assess the association between the use of a digital monitoring tool for hand hygiene compliance and the prevalence of HCAI in the Siem Reap Provincial Referral hospital in Cambodia. The study analyzed 10 wards during the period of 2022-2024 and utilized a generalized linear model for our statistical analysis.

Our study showed a non-statistically significant decrease in HCAI prevalence in the first year of our intervention (OR: 0.83, 95%CI: 0.58-1.20) with a p-value of 0.50. This trend was reversed in 2024 (OR: 1.40 95%CI: 1.06-1.86) with a p-value of 0.02, which we believe to be caused by unmeasured confounding. HH compliance increased from 29% to 64% at the end of the study period. Each 10% increase in correct HH compliance was associated with a non-statistically significant increase of 0.06% in HCAI prevalence (95%CI: -0.10 to 0.22) and a p-value of 0.50. These results suggest that we need to consider methods to further improve the validity of both our HH and HCAI data to mitigate bias and misclassification in our current collection methods.

Background

Hand hygiene (HH) is one of the cornerstones of safe and effective healthcare[1]; it is a cost-effective intervention that helps prevent the spread of healthcare associated infections (HCAIs), which kill over 30 million patients globally every year[2]. The importance of HH to prevent HCAIs had been established by Dr. Ignaz Semmelweis since the mid-1800s when he observed that obstetric patients managed by doctors who had just performed autopsies, had a higher mortality rate than patients managed by midwives. This finding led Dr. Semmelweis to introduce handwashing with a chlorinated lime solution prior to patient contact, which resulted in a dramatic decrease of mortality rate in the poorly performing obstetric clinic from 16% to 3%[1]. Unfortunately, this change was not sustained and Dr. Semmelweis was not able to convince his colleagues of the effect of his intervention. Practice of hand hygiene slowly gained traction, 20 years after Dr. Semmelweis' death, with the introduction of Germ theory by Pasteur, and the concept of antisepsis by Lister[3], however HH compliance remained unacceptably low in both high and low income countries throughout the years[4]. This led to a holistic approach to promote HH compliance that was introduced in 2000 by Pittet et al., which was designed to improve sustainability of interventions aimed at ensuring appropriate HH practice by healthcare workers[5].

Significant progress in improving HH practices has been achieved by leveraging multiple components also known as the multimodal implementation strategy, which aim to support hospitals in addressing logistical, structural and cultural barriers to implementation of an effective HH compliance policy[6]. The multimodal strategy consists of 5 components: 1) access to alcohol-based hand rub at the point of care; 2) training and education of healthcare staff; 3) monitoring and feedback on compliance to appropriate HH practices; 4) visual reminders (i.e. posters); and 5) safe climate through the support of hospital leaders to activities. This strategy has been shown to be effective and long-lasting in numerous settings and models[7–11] and has been applied to our study setting to improve delivery of care.

The Siem Reap Provincial Referral Hospital (SRPRH) is a 470-bed hospital in Siem Reap province, located in northwestern Cambodia, which is a low-middle income country (LMIC) in South-East Asia. The hospital delivers a level 3 Complementary Package of Activities (CPA-3) defined as "a referral hospital which has emergency care services and grand surgery with general anesthesia more than CPA2 (both number of patients and activities) and other specialized services"[12] and is under the direct management of the Siem Reap Provincial Health Department (PHD). SRPRH began the implementation of the multimodal strategy in 2018 with the support of the Diagnostic Microbiology Development Program (DMDP), which is an organization that aimed to improve diagnosis and management of infectious diseases, support infection prevention and control (IPC) practices and enhance the quality of services provided by the microbiology laboratory[13]. HH monitoring compliance activities were unfortunately ceased in 2020 due to the COVID-19 pandemic and the challenges met by the local staff in sustaining monitoring and feedback. HH monitoring activities were officially resumed in March 2023 under the supervision of the Department of Health Services from the Cambodian Ministry of Health (DHS-MoH).

Prior to the cessation of monitoring in 2020, SRPRH relied on direct observation of HH opportunities, which is considered the gold standard for conducting this activity[14]. Direct observation of HH opportunities consists of a hospital staff member in a ward logging information regarding whether other staff members completing their regular duties have washed their hands when the opportunity for doing so arose. The World Health Organization (WHO) define these opportunities as the 5 moments[2], which are: before touching a patient, before performing an aseptic procedure (i.e. inserting a peripheral IV catheter), after touching a patient, after being in contact with bodily fluids, and after touching the patient's immediate surroundings (i.e. bed rails, patient vital sign monitor). Healthcare staff tasked with this activity would write on a data collection sheet[2] each observed opportunity and input this information in an Excel© spreadsheet to visualize trends in compliance.

There are several challenges to performing direct observation as described above, which are particularly relevant to the context of LMICs. The first challenge relates to the availability of human resources to collect data on the ground[14]. Healthcare professionals tasked with monitoring with data collection sheets are tied to this activity until it is completed, the challenge then becomes on deciding whether nurses should be taken away from regular patient-care duties to collect data or whether IPC staff should collect data from every hospital ward. This often leads to conundrums as ward nurses in LMICs are often already overburdened with regular duties, and IPC staff are too few to perform complete data collection from all wards[15]. The second challenge relates to data cleaning and analysis. Data collected on paper needs to be transcribed in a single file, which can be analyzed to identify trends in compliance. The transcription/analysis is done manually using software tools such as Excel© or EpiInfo©, with risk of errors when dealing with a large amount of data[16]. This process is time-consuming and providing feedback in a timely manner is often not sustainable. Finally, direct observation may cause observed healthcare professionals to change their HH practices, which is known as the Hawthorne effect[17], ultimately leading to bias in the data collected.

SRPRH decided to address these challenges with DMDP's technical support using digital monitoring tools. In 2022, DMDP built a data collection form using the KoboToolbox© (https://www.kobotoolbox.org/ Cambridge, MA) application in which the forms were accessible via KoboCollect©. KoboCollect© is a smartphone app that communicates with KoboToolbox©, to fill and send the forms to be stored in a database format. Furthermore, DMDP built a Python© program that automatically analyzed the data to support feedback provision on healthcare worker HH compliance. The activities were successfully piloted at a small scale and an official launch of HH monitoring activities was ratified by both SRPRH and the DHS-MoH in March 2023.

The HH monitoring activities have been sustained to this day and have been rolled out to other referral and national hospitals in the country. It is of interest to know whether these activities have had the intended impact of reducing HCAIs, which has been a challenging problem to address due to lack of surveillance mechanisms[2]. Our primary aim was to utilize available microbiology data from SRPRH during the 2022-2024 period and compare HCAI prevalence before and during HH monitoring activities. Our secondary aim was to assess the presence of an association between increased HH compliance and HCAI prevalence using compliance data collected through KoboCollect©.

This would be the first study in Cambodia to address these questions. The study would be an important milestone to inspire other hospitals to use innovative strategies to monitor HH compliance levels to combat HCAIs. We also hope that this study highlights gaps in intervention implementation to help direct improvement efforts as to better capture how our work has impacted HCAI rates.

Methods

Study design: We performed a pre-post study design assessing the association between HH monitoring activities and HCAI prevalence. The primary exposure was defined as a ward prior to the intervention and the same ward during the intervention. These periods were represented as "before" and "during" implementation of HH monitoring activities respectively. An observation was defined by one ward per month between the period of April 2022 to December 2024, with observations from 2022 constituting the "before" period and those from 2023-2024 as the "during" period. The exposure for our secondary aim was defined as the percent "correct" HH compliance during the intervention period from April 2023-December 2024.

Our HH monitoring tool largely used the WHO observation form (Appendix 1) as a reference with some modification in regards to "HH action". The WHO form lists 4 possible options: HR (hand rub), HW (hand wash), missing (the healthcare staff omitted doing HH), and gloves (the healthcare worker staff was wearing gloves when an HH opportunity arose). Our digital form does not include HW, which is because HW should be done instead of HR for two main reasons: the first reason is that the healthcare worker's hands are visibly dirty and the second reason is that the healthcare worker's hands are at risk of being contaminated with bacterial spores (ie: *Clostridium difficile*). In its current iteration, the WHO observation form does not permit the ascertainment of these two conditions to perform HW and was therefore removed. We also removed "gloves" due to complexities which are beyond the scope of this thesis. Finally, HR was classified in two groups: a "correct" group, which meant that the healthcare worker followed the WHO 6 steps in hand rubbing (Appendix 2) and an "incorrect" group, meaning that hand rubbing was performed but did not follow the WHO 6 steps.

An infection was considered an HCAI if it was deemed clinically significant (see data analysis for more detail on defining clinical significance), and the patient had been admitted for more than 48h[18], which we summed in each ward by month to constitute our numerator. Our denominator consisted of the total number of discharged patients by ward in a month, to which we excluded individuals who were discharged for normal vaginal delivery, whom we expected to have a length of stay (LOS) of less than 48h. HCAI prevalence was therefore defined as the proportion of total hospital acquired infections in a ward per month. We collected data on overcrowding, which we defined as a ward bed-occupancy rate (BOR) higher than 100% in a month[19] (Appendix 3). We also collected data on the total number of microbiology specimens done per month for each ward throughout the study period.We believed that overcrowding and the number of microbiology specimens sent to the laboratory by ward were important covariates, which if not adjusted for, could bias our estimates regarding the association between the HH intervention and prevalence of HCAIs.

Study setting: The intervention was conducted in SRPRH, which is a 470-bed, CPA3 provincial referral hospital that delivers medical, surgical, obstetrics, pediatrics, ICU, and hemodialysis care to the population of the northwestern Cambodian region. The HH monitoring intervention was officially launched in March 2023 and continues to this day. Our study period spans from April 2022 – December 2024, which covers a 9-months period prior to intervention (April 2022-December 2022) and an 18-month period during the intervention (April 2023-December 2024).

Unit of analysis: We evaluated wards from the SRPRH that have participated in the HH monitoring intervention starting in April 2023, after we accounted for a one-month transition period when the monitoring intervention started in March of that year. We excluded wards that were added to the intervention starting from 2024, which were not built prior to April 2022. We included 10 wards in our study and excluded the outpatient and emergency wards in which patients are expected to receive care for less than 48 hours. The following wards were included in our analysis: General Medicine A, General Medicine B, Pneumology 1, Pneumology 2, ICU Medicine, ICU Surgery, GI Surgery, Trauma Surgery, Urology and OB-GYN.

Data collection: We used the HH monitoring data stored on a KoboToolbox© SRPRH user account for our measure of HH compliance. The data on HH compliance is collected by nurses through a Smartphone application called KoboCollect©. While completing their professional duties, nurses observe other professionals, which include doctors, nurses, and midwives, and observe if a HH opportunity arises defined by one of the 5 HH moments as described above. The observed professional may or may not wash their hands, which then gets logged on the KoboCollect© form as “correct” meaning the professional washed their hands and followed the WHO 6 steps in appropriate hand cleaning technique, “incorrect” if the professional washed their hands but did not follow appropriate hand cleaning technique, and “missed” if the professional did not wash their hands. The nurses in charge of monitoring HH compliance were instructed at the beginning of activities to use a convenience sampling scheme to reflect day-to-day practices, by logging opportunities as they were observed, regardless of whether the observed professional had been compliant or not.

To determine the HCAI prevalence numerator, we used the microbiology data generated by the Siem Reap microbiology laboratory from 2022-2024. Doctors who suspect that a patient has a bacterial infection (either community or hospital acquired) can send specimens to the microbiology laboratory for identification and antimicrobial susceptibility testing (AST). All specimens that are processed by the microbiology laboratory, regardless of whether an organism has grown, are entered in CamLIS, which is the online laboratory information system used by government laboratories. The data used in this study was extracted from CamLIS, which provided details for the following selected variables for our analysis: patient ID, type of specimen, sample site, ward provenance, day of patient admission, date of specimen collection, diagnosis, result, and comments on result.

The Hospital Information System (HIS) data was used to determine the HCAI prevalence denominator. The HIS data is collected monthly by the SRPRH administrative office, and provides information on the number of patients discharged in each ward by month, BOR and average LOS. We used diagnostic discharge codes from The HIS dataset to identify vaginal deliveries, which we excluded from the total number of patients at risk for HCAI in the Obstetrics ward. Our decision to subtract vaginal deliveries from the total of discharged patients stems from the assumption that these patients are not expected to stay admitted for >48h.

The study received ethical approval from the University of Washington Human Subjects Division and the Cambodian National Ethics Committee. The study was deemed to not involve human subjects and was therefore waived for an IRB.

Data analysis: We used several steps to define an HCAI in our study. First, we included pathogens known to cause HCAIs in the literature, which were *Escherichia coli*, *Klebsiella spp.*, *Serratia marcescens*, *Acinetobacter spp.*, *Enterobacter spp.*, *Pseudomonas spp., Staphylococcus aureus*, *Coagulase Negative Staphylococcus* (CONS), *Citrobacter spp.*, *Enterococcus spp.*, *Stenotrophomonas maltophilia, Providencia spp.*, *Proteus mirabilis*, *Pantoea agglomerans*, *Ochrobactrum spp.*, *Candida spp.* and *Burkholderia cepacia*[18,20]. We also included in this list *Staphylococcus lugdunensis*[21] and “non-fermenting gram negative rods”. It sometimes occurs that the laboratory may not be able to identify the bacterial species and provides a phenotypic description instead. Our list includes several non-fermenting gram-negative bacteria, which we deemed important to capture under the phenotypical grouping provided by the laboratory.

Following the identification of pathogens known to cause HCAI, we included observations of patients that had a culture collected >48h after being admitted. We considered the date of collection as the date which a physician would have first suspected an infection and sent a microbiology specimen for confirmation. We used the >48h cutoff for the time to which an infection would be considered an HCAI per what has been described in the literature[18].

We removed positive cultures for which the potential for contamination was high. These included positive specimens for CONS from pus swabs, urine cultures and blood cultures. CONS blood cultures were removed from our sample as none grew before 1 day of incubation, and most grew in 1 bottle only[22]. We also removed specimens positive for *Candida spp.* in urine cultures, a genital swab and pus aspirates. *Candida spp.* are commensals in the genitourinary tract and it was deemed that these specimens were more likely to reflect colonization than true infection[23]. Our decision to remove pus aspirates was because of infection with *Candida spp*. does not usually present with skin and soft tissue infection with pus collection[19].

Finally, we underwent a deduplication process using patient IDs to identify when specimens were collected more than once on the same patient. We referred to the National Healthcare Safety Network (NHSN) definition of the Repeat Infection Timeframe (RIT)[24] in which no new infections of the same type are reported within a 14-day timeframe. This entails that if the same pathogen is retrieved from a separate culture <14 days apart, it is not counted as a separate HCAI event. The NHSN guideline also determines that a separate pathogen isolated from the same site (i.e. isolation of both *E. coli* and *Enterococcus spp.* in a urine culture) within a 14-day timeframe does not meet the determination of a new infection[24]. We did not deduplicate events if different pathogens were found in blood cultures with an absence of positive cultures from a site of origin as we could not ascertain that the pathogens were indeed originating from the same site. Pathogens originating from different sites were not deduplicated, however in the case that two of the same pathogens were found (i.e. *E. coli* in a urine and in a blood culture), we compared the antimicrobial susceptibility testing (AST) results of both pathogens and in the circumstance that they were the same, we proceeded to deduplication.

Due to the presence of missingness in some of our observations we performed single-imputation on the following ward-level variables: monthly patient discharge number, average LOS, BOR, average "correct", "incorrect" and "missed" compliance to HH. The HIS data did not include patient discharge data for the Pneumology 2 ward; we inquired the average ward discharge number from SRPRH and created a random distribution of 27 values with a mean of 90 (representing the mean number of discharges) and a standard deviation of 3. We then used these values as the monthly HCAI prevalence denominators for the Pneumology 2 ward.

We used mean substitution for both BOR and LOS data, which both had 2 unlikely values logged into the HIS and were deemed as missing. We replaced these values with the ward-month mean, which was determined by using values from the same ward in the same months to generate a mean value for the missing observation. We also opted for mean substitution for missing HH compliance data but instead of using a ward-month mean, we utilized the adjacent values from the previous and next month of the missing value from the same ward. A total of 20 observations were imputed for 6 wards with most missing values centered around the October-December 2023 period.

We proceeded to use a generalized linear model with random intercepts to account for outcome correlation from observations originating from the same wards. We used the following model for aim 1, with subscript $_i$ representing ward:

$$\text{HCAI}_i = \gamma_{00} + \gamma_{01}\text{Overcrowding}_i + \gamma_{02}\text{Total\_specimens}_i + \beta_3\text{Intervention}_i + U_{0i} + e_i$$

The random intercepts for wards are represented by $\beta_{0i} = \gamma_{00} + U_{0i}$
We modeled Overcrowding and Total_specimens as fixed effects and were included in the model at the ward level.

We made slight changes for plotting purposes using the following model:

$$HCAI_i = \gamma_{00} + \gamma_{01}Overcrowding_i + \gamma_{02}Total\_specimens_i + \beta_3 month\_year_i + U_{0i} + e_i$$

We replaced β_3Intervention$_i$ with $\beta_3$month_year$_i$ to allow visualization of individual months longitudinally across wards. We proceeded in creating three models: a model comparing 2023 and 2024 to a reference of 2022, a model comparing 2023 with 2022 only, and a model comparing 2024 with 2022 only. For our first aim's model we logistically transformed the outcome to avoid predicted HCAI prevalence from being less than zero, which affected plot interpretation. We did so by putting HCAI prevalence on the logit scale and performing exponentiation such that HCAI prevalence percentage values were back on their original scale. We performed the same operations for calculating the odd ratios for our analyses (Appendix 5a and 5b).

For our second aim we used the following model:

$$HCAI_i = \gamma_{00} + \gamma_{01}Overcrowding_i + \gamma_{02}Total\_specimens_i + \beta_3 correct\_HHcompliance_i + U_{0i} + e_i$$

correct_HHcompliance is a continuous variable expressed as a percentage, with a higher percentage representing better compliance to HH practices.

We used odds ratio (OR), which approximated prevalence ratio (PR) as the average outcome of HCAI was less than 5% in our dataset. No adjustments were made for multiple comparisons.

Results

Hand hygiene compliance data:

Compliance data on HH for the 10 audited wards is provided in Figure 1, the dashed vertical line separates the year 2023 from 2024. The average "correct" HH compliance rate for 2023 was 34% and increased to 56% in 2024. Concurrently, there was a decrease of "incorrect" HH compliance from 41% in 2023 to 33% in 2024. A decrease was also observed for "missed" (not performed) HH opportunities from 25% in 2023 to 10% in 2024.

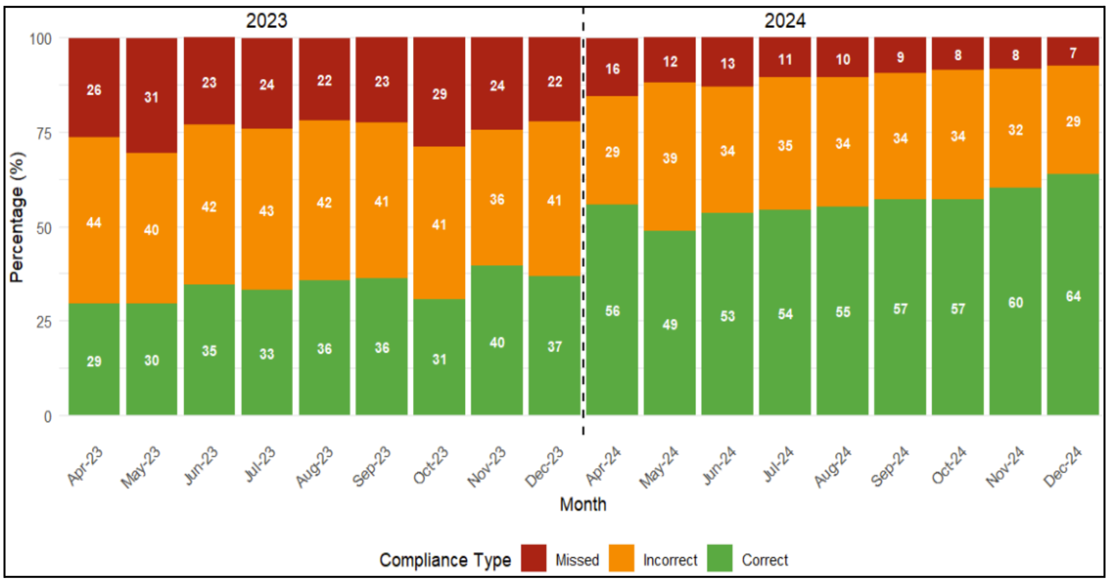

Figure 1: Average Hand Hygiene Compliance Across All 10 Wards (Apr 2023 - Dec 2024).

HCAI prevalence by LOS:

We created a scatterplot for our estimated HCAI prevalence over the patient average LOS shown in Figure 2. We fitted a simple linear regression model (Appendix 4) which showed that for an increase of 1 day of LOS the %HCAI prevalence increased by 0.62% (95%CI: 0.44-0.80, p-value <0.05). The average monthly LOS is represented by the total number of inpatient days divided by the number of discharges and deaths in each month.

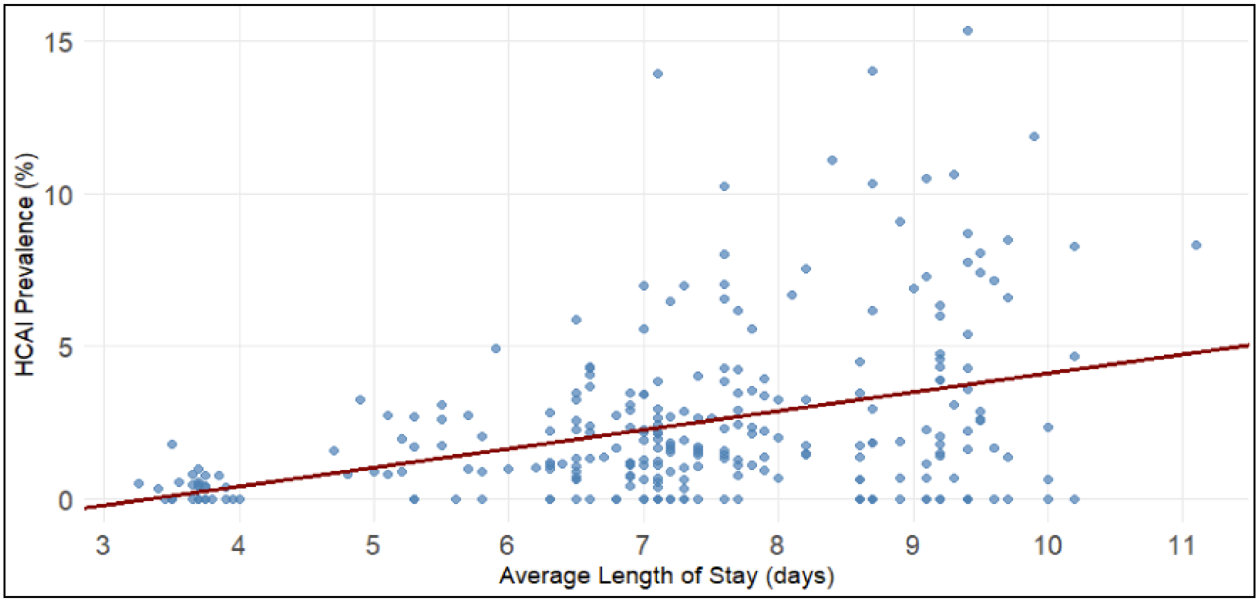

Figure 2: HCAI Prevalence by Average Length of Stay

HCAI prevalence by year:

Figure 3 shows a fitted Locally Weighted Scatterplot Smoothing (LOWESS) plot of %HCAI prevalence over the duration of our study period. Visual inspection of the LOWESS curve reveals a small decrease of %HCAI prevalence in 2023 compared to 2022, however this trend is reversed in November 2023. In 2024, the %HCAI prevalence was higher than either 2022 and 2023.

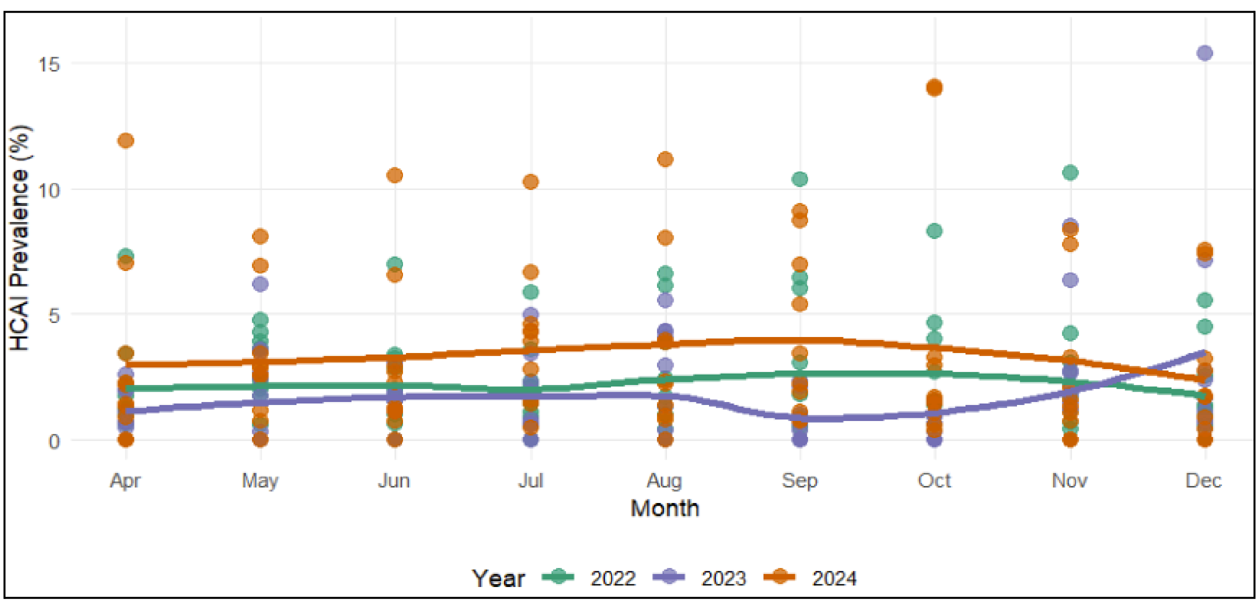

Figure 3: LOWESS plot of HCAI prevalence over the 2022-2024 period

HCAI prevalence before and during the HH monitoring intervention:

Table 1 provides the adjusted estimates for the prevalence rate of HCAI based on the period when the HH monitoring activities were deployed.

Intervention period	Adjusted HCAI OR (95%CI) *	P-values
2023-24 vs 2022 (ref)	1.10 (0.84-1.45)	0.49
2023 vs 2022	0.84 (0.58-1.21)	0.35
2024 vs 2022	1.41 (1.06-1.87)	0.01

Table 1: HCAI OR comparing periods before and after HH monitoring intervention
**: Adjusted for Overcrowding and Total number of specimens*

Comparing the 2023-2024 period with 2022, the adjusted HCAI OR was 1.10 (95%CI: 0.84-1.45, p-value: 0.49) showing that there was no statistically significant change in HCAI odds between the two periods. We observed a non-statistically significant decrease in the odds of HCAI when comparing 2023 with 2022 with an HCAI OR of 0.84 (95%CI: 0.58-1.21, p-value: 0.35). This trend is however reversed when comparing 2024 with 2022 with an HCAI OR of 1.41 (95%CI: 1.06-1.87, p-value: 0.01), meaning there was 41% increased odds of HCAI in that period.

In Figure 4 we observed that the rate of HCAI differed between wards with prevalence of HCAIs that was above 10% in both ICU surgery and Urology and less than 1% in OB-GYN. A decrease in HCAI rate can be observed during the August-September 2023 period across all wards, 4 months after the beginning of our intervention in April 2023 (vertical dashed line), with a reverse in the trend occurring in November-December 2023.

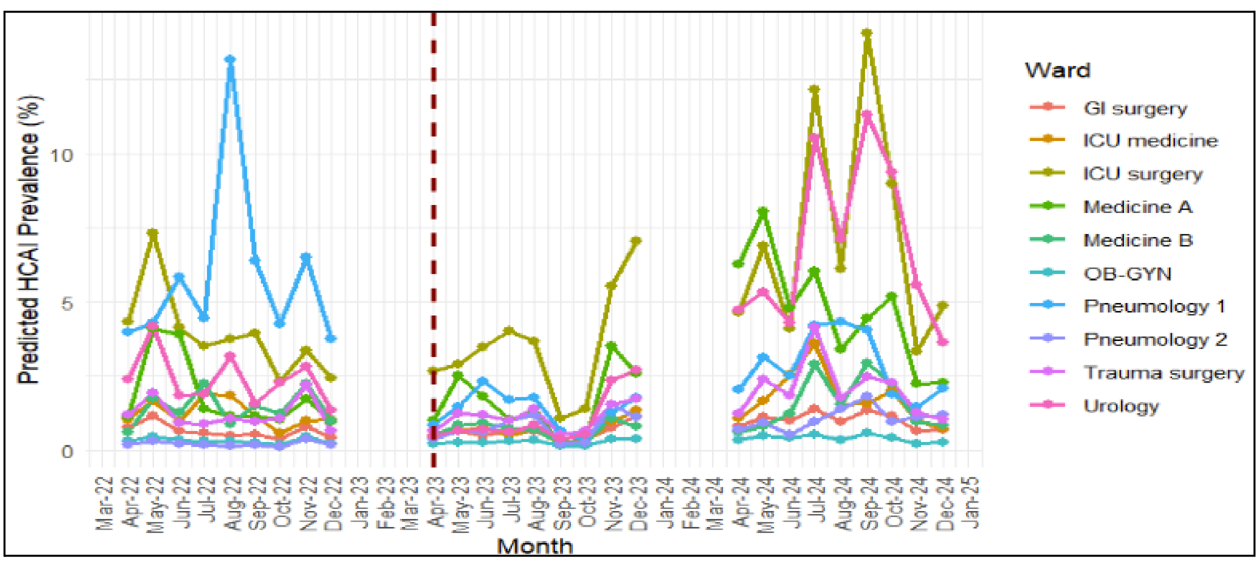

Figure 4: generalized logistic mixed-effect linear model of HCAI prevalence in the 2022-2024 period

HCAI prevalence and correct HH compliance:

Table 2 shows the association between HCAI prevalence for each 10% increase in HH compliance adjusted for overcrowding and total number of specimens.

%HCAI prevalence for every 10% increase in HH compliance (95% CI) *	P-value
0.06 (-0.10 to 0.22)	0.50

Table 2: Association between correct HH compliance and HCAI prevalence (2022-2024)
**: Adjusted for Overcrowding and Total number of specimens*

For each 10% increase in compliance to HH, we fail to observe a statistically significant relationship with HCAI prevalence. For each 10% increase in HH compliance, HCAI prevalence increases by 0.06% (95%CI: -0.10 to 0.22, p-value: 0.50). This trend is observed in all wards as shown in Figure 5. For plotting purposes, we removed Overcrowding as it did not significantly change the HCAI prevalence change after running sensitivity analyses.

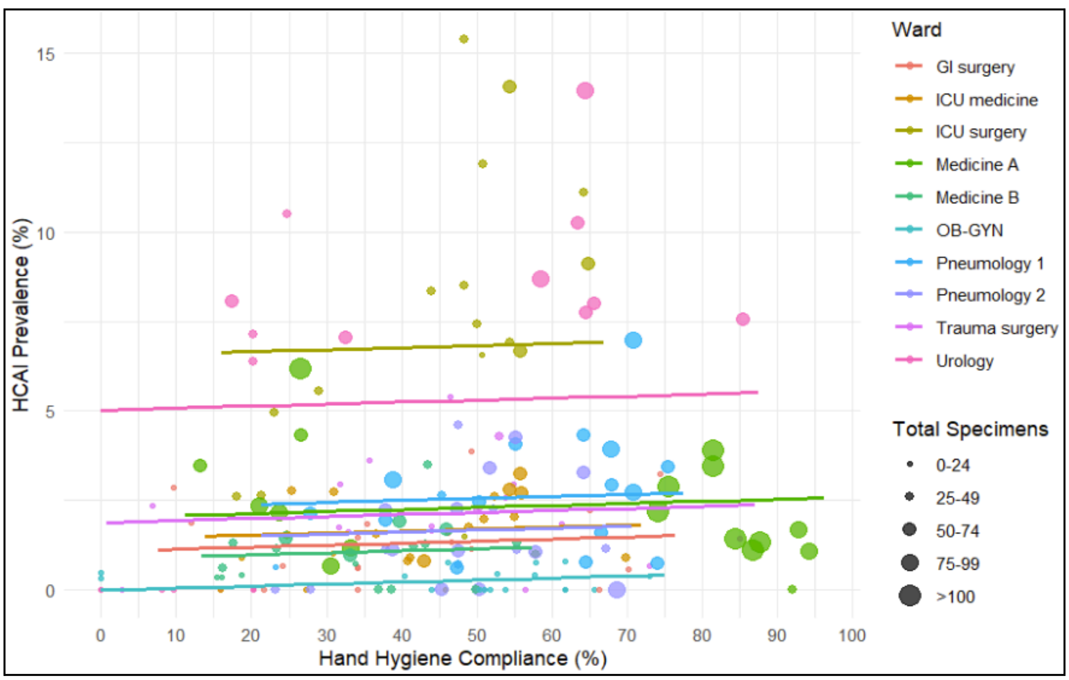

Figure 5: %HCAI prevalence change based on percentage of correct compliance to Hand Hygiene

Discussion

This study examined the impact of HH monitoring activities on HCAI prevalence in a provincial referral hospital in Cambodia. We observed a non-statistically significant decrease in HCAI prevalence rate in the year that activities were implemented followed by a subsequent statistically significant increase in the following year. Paradoxically, we observed that hand hygiene compliance increased in the 2024 period from an average correct compliance of 33% in 2023 to 54% in 2024. This paradox could be explained by the fact that the data collected by ward nurses on HH compliance is not validated, which could lead to the data being affected by selection bias[2]. In this circumstance, the systematic selection of certain times, care situations, health-care workers or opportunities for observation can lead to results that do not reflect overall hand hygiene compliance. Furthermore, our data showed that correct HH compliance was not associated with change in HCAI prevalence, which we would have expected to decrease based on the literature and reinforces the possibility of selection bias in the collection of HH compliance data.

There was an increase of HCAI prevalence in 2024 in comparison to 2022, which may be explained by a number of factors. The hospital inaugurated a new building housing multiple wards in December 2023, which led to a temporary halt of HH monitoring activities in the period between October-December 2023, which was reflected in our data with presence of missingness for 6 of the 10 audited wards in that same period. The pause on monitoring activities was correlated with an increase in HCAI prevalence, which unfortunately did not come back to previous levels after monitoring activities were re-established for those wards in January 2024. We also need to consider the likely presence of unmeasured confounders, which may have led to the increase in HCAIs. The highest rates in infections were observed in ICU surgery and Urology and could have been due to the implementation of invasive practices in the later periods of our study, which could have put patients at increased risk to HCAIs.

The use of digital tools for HH monitoring has been described by Wiemken et al. in a study carried in the United States in 2018[16]. The authors used Google Forms (Alphabet Co. Mountain View, CA) for data collection and R for data analytics. The authors noted the issue with lack of HIPAA-compliance using Google platforms for the collection and storage of protected health information. Similarly to Google Forms, KoboToolbox's public servers are not inherently HIPAA-compliant, which may be a hindrance for some centers who may wish to use digital tools for monitoring but who may have concern about patient confidentiality. The authors also relate limitations in regards to linking data collection forms with the R program, which require variables to be named as specified by the code. Hospitals who wish to use our Python© program also need to be onboarded to be able to launch the program from their computer, however once all dependencies are installed and staff trained, the IPC staff do not have to worry with what happens under the code's hood and can launch the code in a similar fashion as launching an executable program. Our program offers the same flexibilities as what described by Wiemken et al. in regards to the specific type of moment collected, which can be analyzed as separate subsets by the Python code.

Our results differ from what has been described in the literature. Pittet et al. describe a statistical significant decrease in overall HCAI prevalence from 16.9% to 9.9% (p-value = 0.04) with the concomitant increase in HH compliance from 48% to 66% (p-value <0.001)[5] in a teaching hospital in Geneva, Switzerland. Similarly to our setting, the study implemented the multimodal strategy, which included monitoring and feedback through the direct observation of ward staff, logging HH opportunities as they arose. Specifically, monitoring was performed with seven surveys done twice yearly between 1994-97. Comparable results have been described by a study by Salama et al. in a Kuwaiti teaching hospital[25], which used a similar intervention approach to Pittet et al. Sickbert-Bennett et al.[26] described that even for very high HH compliance rates, HCAI rates are shown to decrease as well, although their methodology consisted of direct observation of HH before and after entering a patient's room. HH compliance rates in our study showed that healthcare professionals improved their HH practices from an average correct compliance of 34% in 2023, which increased to 56% in 2024.however our study failed to show any statistically significant association with HCAI prevalence, which we believe may be caused by bias in HH data collection.

This is the first study to be done in Cambodia looking at the association between HH monitoring activities and HCAI prevalence. The goal for conducting the HH monitoring activities was to establish a proof of concept, showing that digital monitoring activities can be sustainably carried in LMICs, which continue to be implemented to this day. This study went a step further and aimed at assessing whether these activities impacted HCAI prevalence in our setting; however our data showed a non-statistically significant decrease in HCAI prevalence in 2023. Although our study did not demonstrate a statistically significant impact on HCAI at this stage, we would continue to recommend monitoring of HH. The monitoring activities do not come at a cost to the hospital as KoboCollect©, KoboToolBox© and the Python© code are free to use and do not require complex IT maintenance overhead. Furthermore, HH monitoring is a well-established quality indicator for hospitals[2], and the use of digital tools saves time for auditors who do not have to log opportunities with a pen and paper and IPC staff who can automatically extract results without needing to pre-process the data for analysis[16].

Another strength of our study stems from the variables in our HH monitoring tool. We removed variables which we did not think were critical for assessing compliance, such as hand wash, and added precision by separating correctly versus incorrectly performed HH. The WHO HH monitoring form and previous studies[5,25,26] have not made the distinction between "correct" and "incorrect" HH, however we think that monitoring correctness aligns with current recommendations of proper HH practice. Our study shows that it is feasible to report on correctness of HH practice and would suggest that future studies consider adding this layer of precision as it may provide interesting answers to scientific questions such as whether following the WHO 6 steps is associated with decrease of HCAI rate versus performing "incorrect" HH.

This study highlights important caveats which need to be addressed to demonstrate the impact of HH monitoring on HCAI prevalence. Potential selection bias in the collection of HH data by ward nurses, could be mitigated through a validation mechanism. The WHO guidelines on Hand Hygiene in Health Care recommend having trained observers perform parallel observations and compare results[2] and the integration of such a mechanism would allow the IPC team to ensure that the collection process reflects the reality on the ground in regards to HH compliance. Furthermore, the WHO guidelines recommend the use of kappa scores to provide reproducible quantitative data, which can be a solid foundation for subsequent discussion for learning purposes to ultimately reach concordance[2].

The method used to evaluate HCAI prevalence in our study is another limitation inherent to our study. Cambodia does not, at this stage, have a surveillance mechanism for assessing rates of HCAI, and we used the Siem Reap hospital microbiology and HIS data as a proxy to answer our scientific question. We did not have patient-days data, which may have either over or underestimated HCAI prevalence in our study. It is also important to note that not all patients with an HCAI will have a positive microbiology sample and may be diagnosed syndromically, which may lead to underestimation of HCAI prevalence. HCAI surveillance is difficult[27] to achieve in developing countries due to the lack of human resources and expertise in infectious diseases and hospital epidemiology. We believe that we made reasonable efforts to define HCAI outcome using microbiology data however our study would have greatly benefited from an HCAI surveillance system.

We cannot rule out the possibility of misclassification of HCAI outcome in which positive microbiology specimens reflect late collection in patients with community acquired infections rather than true HCAI. We made significant efforts to reduce this bias, which is reflected in the positive correlation between HCAI outcome and average length of stay in our dataset. An infection after a length of stay of >48h is necessary to establish the diagnosis of HCAI and it is expected to observe an increase in HCAI prevalence in wards where patients have a longer average length of stay. We do not think that the fluctuations in HCAI prevalence are due to seasonality. We parsed our data over 3 years and compared each 9-month period to ensure similarity across periods.

This study provides insights on the challenges that can arise when monitoring HH compliance in a LMIC setting. The digital tools used to collect HH opportunities have been a first step in ensuring sustained data collection by ward staff, however biases may negatively affect both HH compliance and HCAI data in our study. The use of digital tools for data collection has been demonstrated in LMICs[28], which could be leveraged to monitor HH compliance, however healthcare centers in LMICs should not lose sight of the various threats to validity that may be unique to their setting. This study aims to demonstrate that even though an intervention may be successful in its own right, we must address issues that may subsequently arise and devise solutions to ultimately reach our goal of improved patient care and safety.

We propose a "validation layer" that would require the IPC team to collect data on a small number of opportunities, which would then be compared to a randomly selected batch of opportunities collected by ward staff. The established use of digital tools for this work makes the integration of a validation layer a possibility and we believe this is an elegant next step in improving HH compliance monitoring. This leverages both the large number of opportunities collected by ward staff and the mitigation of bias by the IPC staff, who verify that what is reported by staff is indeed concordant with what the IPC staff has observed.

In conclusion, although our study did not show a statistical change in HCAI prevalence comparing our intervention period (2023-2024) with our pre-intervention period (2022) we believe that continuing HH monitoring, using digital tools, is an important foundational step to address HCAIs. Our study gives valuable insights on the next steps to improve HH monitoring activities, which can be achieved with the use of validation mechanisms for the assessment of HH data, and the establishment of an HCAI surveillance tool to provide more precise data on infection rates.

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Appendix

Appendix 1: WHO HH observation form.

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Observation Form

Facility:		Period Number*:		Session Number*:	
Service:		Date: (dd/mm/yy)	/ /	Observer: (initials)	
Ward:		Start/End time: (hh:mm)	: / :	Page N°:	
Department:		Session duration: (mm)		City**:	
Country**:					

Prof.cat			Prof.cat			Prof.cat			Prof.cat		
Code			Code			Code			Code		
N°			N°			N°			N°		
Opp.	Indication	HH Action	Opp.	Indication	HH Action	Opp.	Indication	HH Action	Opp.	Indication	HH Action
1	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	1	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	1	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	1	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves
2	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	2	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	2	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	2	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves
3	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	3	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	3	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	3	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves
4	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	4	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	4	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	4	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves
5	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	5	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	5	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	5	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves
6	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	6	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	6	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves	6	☐ bef-pat. ☐ bef-asept. ☐ aft-b.f. ☐ aft-pat. ☐ aft.p.surr.	☐ HR ☐ HW ○ missed ○ gloves

Appendix 2: WHO 6 steps to correct hand hygiene using alcohol hand rub.

Appendix 3: calculation of overcrowding per ward/month:

(Number of patient days * 100) / (Number of beds * number of days in month)

Appendix 4: linear model formula used for figure 2

$$\textbf{HAI\_prevalence} = \beta 0 + \beta 1\textbf{Average\_LOS}$$

Results:

lm(formula = HAI_prevalence ~ average_LOS_days, data = completed_dataset)

Residuals:

Min	1Q	Median	3Q	Max
-4.2396	-1.5423	-0.3710	0.7842	11.6356

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2.07363	0.68578	-3.024	0.00274 **
average_LOS_days	0.61894	0.09192	6.733	1.01e-10 ***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.578 on 268 degrees of freedom
Multiple R-squared: 0.1447, Adjusted R-squared: 0.1415
F-statistic: 45.34 on 1 and 268 DF, p-value: 1.005e-10

	2.5 %	97.5 %
(Intercept)	-3.4238339	-0.7234255
average_LOS_days	0.4379628	0.7999168

Appendix 5a: Generalized linear model with correlated outcome regression for aim 1 comparing 2023-2024 to 2022 (ref) using the lme4 library in R (version 4.4.1).

```
library(lme4)

completed_dataset$logit_HAI <- log((completed_dataset$HAI_prevalence/100 + 0.001)/(1.001 - completed_dataset$HAI_prevalence/100))

logit_model_i <- lmer(logit_HAI ~ intervention + Overcrowding + total_specimens + (1 | Ward),
                data = completed_dataset)

logit_model_i
model_summary <- summary(logit_model_i)

fixed_effects <- fixef(logit_model_i)
fixed_effects_se <- sqrt(diag(vcov(model_summary)))
fixed_effects_pval <- 2 * (1 - pnorm(abs(fixed_effects/fixed_effects_se)))

model_ci <- confint(logit_model_i, method = "Wald")
print(model_ci)

odds_ratios <- data.frame(
  Parameter = names(fixed_effects),
  Estimate = fixed_effects,
  SE = fixed_effects_se,
  OR = exp(fixed_effects),
  CI_lower = exp(model_ci[names(fixed_effects), 1]),
  CI_upper = exp(model_ci[names(fixed_effects), 2]),
  p_value = fixed_effects_pval,
  Significance = ifelse(fixed_effects_pval < 0.001, "***",
               ifelse(fixed_effects_pval < 0.01, "**",
               ifelse(fixed_effects_pval < 0.05, "*",
               ifelse(fixed_effects_pval < 0.1, ".", ""))))
)

odds_ratios$p_value_formatted <- format.pval(odds_ratios$p_value, digits = 3)
print(odds_ratios)
```

Appendix 5b: Output from the generalized linear model for aim 1 (2023-2024 versus 2022).

Linear mixed model fit by REML ['lmerMod']

```
Formula: logit_HAI ~ intervention + Overcrowding + total_specimens + (1 | Ward)
Data: completed_dataset
REML criterion at convergence: 845.2544
Random effects:
  Groups    Name         Std.Dev.
  Ward      (Intercept)  0.8455
  Residual               1.0769
Number of obs: 270, groups:  Ward, 10
Fixed Effects:
    (Intercept)  interventionduring  Overcrowdingyes   total_specimens
       -5.70191          0.09823          -0.06902              0.03271
```

```
                           2.5 %     97.5 %
.sig01                       NA         NA
.sigma                       NA         NA
(Intercept)          -6.3572957 -5.04651946
interventionduring   -0.1772175  0.37368566
Overcrowdingyes      -0.3597174  0.22167903
Total_specimens       0.0259107  0.03951105
```

Parameter	Estimate	OR	CI_lower	CI_upper	P_value
(Intercept)	-5.701	0.003	0.001	0.006	<0.05
Intervention during	0.098	1.103	0.837	1.453	0.485
Overcrowdingyes	-0.069	0.933	0.697	1.248	0.642
total_specimens	0.032	1.033	1.026	1.040	<0.05