Sensor-Based Electronic Monitoring Systems: Impact on Healthcare-Acquired Infections and the Role of Sensor Placement

Introduction/Background

Healthcare-Acquired Infections (HAIs), also known as nosocomial infections or hospital-acquired infections, are infections contracted by patients while receiving care in medical facilities. To date, they remain among the most common adverse events in hospitals, ranking in the top five causes of death in the United States (Haque, Sartelli, McKimm, & Abu Bakar, 2018). In 2017 alone, over 1.7 million cases of HAIs were associated with over 99,000 deaths and an estimated $6.5 billion in costs (Dufour et al.,2017). While several preventative strategies have been explored over the past twenty years, the hands of health care workers (HCWs) are considered primarily responsible for the transmission of bacteria responsible for HAIs. As a result, good hand hygiene (HH) is considered one of the most effective interventions for reducing HAIs.

The World Health Organization Patient Safety Guidelines (2009) have provided a foundation for HCWs, administrators, and authorities by offering scientific evidence, evidence-based recommendations, and implementation strategies for hand hygiene compliance (HHC). One of the most widely adopted parts, still utilized and referenced in literature today is the "Five Moments for Hand Hygiene," which defines the key times that HCWs should clean their hands to prevent transmission of HAIs. Presently, these patient safety guidelines and the Five Moments have continued to be in place in modern studies. Recent events such as the coronavirus epidemic in 2019 have renewed the interest in extending HH research (Doufour et al.,2017). Additionally, hospitals have been further incentivized to increase HHC rates, as payers have increasingly been denying reimbursements to hospitals for avoidable complications such as HAIs (Cure et al., 2013).

With modern advancements in technology, new approaches have emerged to monitor and improve HHC. One of these new technologies is sensor-based electronic monitoring systems (EMS). However, as a relatively new approach for monitoring HHC, the implementation of these EMS systems varies widely. The lack of standardization in how sensors are placed in existing studies, as well as differences in sensor types, study types, and hospital settings make it difficult to compare findings. Furthermore, very few studies examine the impact of these EMS systems on reducing HAIs.

This literature review compiles and summarizes the existing literature on sensor-based EMS systems for HH, emphasizing two main gaps: (1) the limited evidence connecting EMS implementation with improved HAI outcomes, and (2) the lack of standardized methods for sensor placement and study design. These gaps are relevant to the upcoming implementation of SwipeSense, a sensor-based EMS, in an Emory research project focused on the post-anesthesia/preoperative care unit (PACU/pre-op unit) over the Fall 2025 Semester.

Monitoring Hand Hygiene Compliance (HHC)

Existing Measures for HHC

Direct (visual) observation is widely regarded across multiple sources as the "gold standard" HHC, as it captures the most detailed information on hand hygiene (HH) events (Mouajou et al. 2022). However, despite the higher quality of information that can be collected, only a small fraction of HH opportunities

is observed. This method is also biased by the Hawthorne effect (Kelly et al., 2021), where healthcare workers (HCWs) temporarily increase HH compliance when they know they are observed, which results in inflated and representative compliance rates. Direct observation studies are also time-consuming, costly, and do not provide continuous monitoring.

Dufour et al. (2017) describe three other methods for monitoring HHC. Self-reporting is resource-efficient but is limited by reporting bias and data validity. Video surveillance can limit observational bias, but is also time-consuming, raises privacy concerns, and is not real-time. Alcohol-based hand rub consumption provides an indirect measurement of HH activity but does not measure compliance at the individual level.

Sensor-Based Electronic Monitoring Systems

Sensor-based electronic monitoring systems (EMS) provide an alternative for monitoring HHC, addressing many limitations of other existing measures.

These systems allow for the observation of a larger group of healthcare workers and offer a more thorough picture of hand hygiene across the hospital settings, with more precise location and time-specific details (Kelly et al., 2021). In addition to the automated collection of data from sensors, these EMS systems enable automatic uploading and analysis of hand hygiene data to predict infection trends and generate reports. Moreover, these systems provide local real-time reminders to healthcare workers at the point of care to improve hand hygiene compliance.

Despite these advantages, EMS systems also have their drawbacks. They cannot capture more granular data such as the duration or thoroughness of HH events, and compliance may still be affected by the Hawthorne effect if staff are aware of being monitored (Mouajou et al., 2022).

Analysis of Existing Literature on Sensor-Based Electronic Monitoring Systems

An analysis of the existing literature on sensor-based EMS systems reveals a large diversity of technological approaches and evaluation metrics. Sensor systems range from ceiling-mounted antennae to wearable badge systems with chemical and proximity sensors, to trackers placed to monitor HCW enter-exit patterns that provide feedback with visual color lighting on personal badges, above-patient lighting fixtures, and voice prompts. While many studies of sensor-based EMS systems do exist, none specifically focus on where the sensors were placed within the hospital environment, and very few have evaluated the impact of these EMS systems on reducing HAIs.

The table on the following page summarizes the key peer-reviewed studies on the applications of sensor-based EMS systems, and highlights sensor types, approaches, and outcomes.

Overall Analysis

Analysis across existing literature shows that the implementation of sensor-based EMS systems takes many forms and has been tested in a wide range of hospital settings. Studies range from comparison of EMS systems to direct observation methods in individual units, to linking a causal relationship with EMS systems to hand hygiene compliance across entire hospitals. Despite the wide range of studies across literature, most reported substantial increases in HHC after EMS implementation.

Impact on Hand Hygiene and Healthcare-Acquired Infections

Across almost all studies, it is suggested that the implementation of sensor-based EMS technology leads to improved compliance. However, very few studies were specifically designed to evaluate the direct impact of EMS systems on reducing HAIs. The few studies that did report impacts on HAIs did not link a causal relationship to the implemented EMS systems.

Sensor-Based Electronic Monitoring System	Sensor Type + Locations	Intervention	Study Setting	Study Type	Effect on HHC	Effect on HAIs
3M System (Venkatesh et al., 2008)	Hand sanitizer mounted sensor at room entrance for HCW entrance/exit monitoring	Audio Prompt (3 beeps, "Please wash your hands"), Visual Prompt (Flashing Lights)	12 Patient Rooms in a Medical Center	Quasi-Experimental Study	Overall HHC increase from 36.3% to 70.1%	Average of 1.0 horizontally transmitted VRE infection per month, vs preceding 4.7 in last 6 months and 3.6 in past 12 month
Amron Corporation System (Swoboda et al., 2004)	N/A	Vocal Prompt	14-bed, 9 room Intensive Care Unit	3-Phase Quasi-Experimental Study	First phase with voice prompting led to 37% improvement, second phase after voice prompting led to 41% improvement	Decrease in 22% of HAIs during voice prompting phase, and decrease in 48% after voice prompting phase
BioVigil (McCalla et al., 2017)	Chemical Sensors for Alcohol Rub usage, Physical sensors for sink distance, Above-the-door sensors for entrance/exit tracking, HCW ID tags	ID badges would turn green, yellow, or red. Audio Prompt	292 bed community hospital's ICU and ICU stepdown unit	Quasi-experimental Study	95.2% compliance in ICU (compared to observed 98.8%), and 96.7% (compared to 99%) in ICU stepdown	ICU: Decrease in MRDOS from 2/1,000 patient days to 0.4/1000 patient days, elimination in CLABSI ICU Step down: Decrease in MRDOS from 1.3/1,000 patient days to 0.8/1000 patient days, elimination in CLABSI Neither of finding statistically significant
Tork Vision (Kelly et al., 2021)	Antennae mounted on ward ceiling, HCW ID tags, internet connected AHR	Real-time HHC feedback to wall mounted screen and individual smartphone/tablet	Acute NHS Trust (31 bed medical ward)	Quasi-experimental Study	N/A	N/A
Unknown IoT System (Xu et al., 2021)	Regional signal transmitters (track HCW enter/exit, clean/contaminated areas, washed areas), Liquid bottle sensors (next to each bed), Sensor device to track ward entrance/exit, HCW ID tags	ID badges would turn green, yellow, or red.	19 bed Emergency ICU Ward	Observational Study	28% increase in HH before contacting patients, 14% increase after contacting patient	No change in acinetobacter baumannii, klebsiella pneumoniae, staphylococcus aureus and pseudomonas aeruginosa
Unknown HH System (Genesero et al., 2022)	Liquid bottle sensor, Bedside sensor, "Invasive Device" sensors for Central Venous Line and Urinary Catheters, HCW RFID badges,	Green/red flashing light above patient bed	4 rooms in research hospital medical surgical unit	Controlled experimental Study	59% HHC with general sensors, 69.5% with the invasive sensors	N/A
MediHandTrace (Dufour et al.,2017)	Sensors in shoes read at either alcohol rub dispensers outside or inside the room, sensors to track area around patient bed using antennae.	N/A	17-bedroom Infectious Disease ward	Observational Study	Overall HHC increase	No Direct Evidence Provided
DebMed (Kelly et al., 2016)	Generic Alcohol/soap dispenser sensors	N/A	23/28 Inpatient units in a teaching hospital	Retrospective Analysis	25.5% increase in HHC	0.114/1000 patient days decrease in MRSA
DebMed (Leis et al., 2020)	Alcohol/soap dispenser sensors	N/A	26 units associated with 746 beds across 5 hospitals	Stepped wedge cluster randomized study	52% Improvement	Acknowledge association of decreased HAIs, but not statistically significant.
ZigBee System (Fihlo et al., 2014)	Bedside sensor, handwash sensor	Green/red light flashing above patient bed	Adult Step-down Unit	Observational Study	Showed sensor was aligned with observational study counts	No Direct Evidence Provided

Lack of Sensor-Placement Standardization

Studies varied widely in sensor type, location, and placement strategy, and most did not clearly describe their methodology for sensor positioning. This lack of standardization makes it difficult to compare results across studies and limits the ability to identify best practices for maximizing HHC.

Discussion: The Impact of Sensor-Based EMS Systems on Healthcare-Acquired Infections

Although all reviewed studies reported increases in hand hygiene compliance (HHC) after the introduction of sensor-based EMS systems, few evaluated the impact of these systems on HAIs. Furthermore, none of these studies were able to define a causal relationship between EMS implementation and reductions in HAIs. This highlights the broader challenge of linking HHC improvements to infection outcomes, regardless of the technology used to improve HHC.

Inconsistencies defining HHC also contribute to this challenge, as compliance is measured in different ways, with inherent variability based on location. For instance, Venkatesh et al. (2008) reported a baseline compliance rate of 36.3% in a 12-room medical center, while Xu et al. (2021) reported a baseline compliance rate of 75.% for nurses alone in an emergency ICU unit. Furthermore, even if HHC improves, HAIs are influenced by multiple other factors, such as environmental conditions and adherence to other infection control policies.

In the context of the implementation of the SwipeSense EMS system at Emory's PACU/pre-op unit, a more quantitative design could be used to evaluate the impact of the EMS system on HAI outcomes. One approach could be a multiple-baseline design to track pre-/post-intervention data cycles, while comparing subsections of the unit for HAI outcome differences. However, this design approach may lead to multiple months of implementation, which may be outside of the scope of the research period.

Discussion: Impact of Sensor Locations on Sensor-based EMS Systems

Placement of Sanitation Dispensers

Because sensor placement location varies with the types of sensors used, the existing literature provides limited information on optimal sensor positioning. However, literature does exist on the evaluation of the placement of sanitization dispensers, which can be used to guide the sensor placement. A study by Cure et al. (2013) conducted an evaluation of optimal sanitization dispenser placement, beginning with qualitative measures and then translating them into quantitative factors to develop a simulation-based method to determine optimal dispenser locations.

This study identified four ergonomic principles to guide dispenser positioning:

- Importance: Dispensers should be placed in convenient workflow-centered locations.
- Frequency: Frequently used dispensers should be placed at convenient locations.
- Fundamental: Dispenser components should be arranged according to their function.
- Sequence of Use: Dispenser components should follow a logical sequence to support sequential operations.

In addition to evaluating positioning, Cure et al. also propose three evaluation criteria:

- Usability: The degree to which dispenser placement integrates with workflow use

- Standardization: Consistency in the number and positioning of dispensers installed in a standardized unit.
- Conformity: Alignment with regulations and organizational policies.

These qualitative measures and evaluation criteria were then used to model common patient-care workflows and identify candidate locations for dispensers. Through simulation, researchers were able to assess how dispenser placement influenced ease of use, compliance potential, and overall workflow efficiency.

Addressing the Gap: Dispenser Placement Research to EMS Sensors at Emory

While the work of Cure et al. (2013) provides a framework for evaluating dispenser placement, similar approaches can be utilized to determine optimal locations for SwipeSense Sensors in the PACU/Pre-op unit at Emory:

- Qualitative Experience and Process Mapping: Documenting the most common steps healthcare workers take and decision points in their workflows that influence hand hygiene opportunities.
- User interviews and feedback: Collecting input from a wide range of HCWs, including nurses, physicians, and support staff to capture multiple perspectives on workflow needs.
- Ergonomic placement: Ensuring dispensers and sensors are installed at convenient heights, near points of care, and in logical sequences that support efficient operations.
- Evaluation of potential locations: Ensuring dispensers and sensors are placed in usable locations that are standardized throughout the unit while conforming to regulations and organizational policies.
- Simulation modeling: Use simulation techniques to model HCW movement within the ward, test candidate sensor locations, and predict compliance outcomes.

For Emory's adoption of SwipeSense, integrating these methods would provide a more evidence-based approach to sensor placement. By combining workflow simulations with staff feedback and ensuring adherence to regulatory standards, this project could maximize compliance rates while also supporting staff acceptance and long-term sustainability of the system. Additionally, the scope of this implementation is more feasible within the timeframe of this project's scope.

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Search Log			
Search Strategy	Database	Number of Results	Most Relevatn Article Citaiton/Notes
(“nosocomial infection” OR “hospital-acquired infection” OR “hospital acquired infection” OR “hospital infection” OR HAI OR “clinical infection”) OR “hospital-onset infection”) AND (“hand hygiene” OR “handwashing” OR “hand washing” OR “hand sanitization” OR “hand disinfection” OR “hand antisepsis” OR “hand sanitizer”);	Web of Science	383	Hand hygiene compliance in the prevention of hospital-acquired infections: a systematic review Literature review from 2022. Reviews existing literature to determine the optimal threshold for HCW HHC rate associated with lowest HAI incident rate. References 35 other articles studies, with most studies reporting lower HAI rates with HHC rates of crater than 60% Overall, trends were analyzed without any inferred causality. Evidence still needed to determine the specific targets for HHC rates
(“hand hygiene compliance” OR “hand hygiene adherence” OR “handwashing compliance”) AND (“electronic monitoring” OR “automated system” OR “sensor-based system” OR “electronic compliance”)	Web of Science	26	Electronic hand hygiene monitoring systems can be well-tolerated by health workers: Findings of a qualitative study Article discussing the realized importance of hand hygiene and embracing technology to improve adherence. Conflicting opinions about automated readings (accuracy, alignment with existing systems, clinical decisions) and the utilization of automated feedback.
(“IoT” OR “Internet of Things” OR RFID OR Bluetooth OR RTLS OR “ sensor” OR “sensor network”) AND (“hand hygiene compliance” OR “hand hygiene monitoring” OR “handwashing tracking”)	Pub Med	20	Comparison of two electronic hand hygiene systems using real-time feedback via wireless technology to improve hand hygiene compliance in an intensive care unit Evaluating HHC through RFID badges and an invasive device sensor, proving an invasive device sensor results in better HHC while using a feedback loop system
(“sensor placement” OR “sensor location” OR “dispenser location”) AND (“hand hygiene” OR “handwashing” OR “hand washing” OR “hand sanitization” OR “hand disinfection” OR “hand antisepsis” OR “hand sanitizer”) All yrs	Pub Med	4	A survey of commercially available electronic hand hygiene monitoring systems and their impact on reducing healthcare-associated infections Identification of Electronic HH monitoring systems, and an overview of what exists and how designs were evaluated.
(“IoT” OR “Internet of Things” OR RFID OR Bluetooth OR RTLS OR “ sensor” OR “sensor network”) AND (“hand hygiene compliance” OR “hand hygiene monitoring” OR “handwashing tracking”) AND (“nosocomial infection” OR “hospital-acquired infection” OR “hospital acquired infection” OR “hospital infection" OR HAI OR "clinical infection" OR "hospital-onset infection")	Pub Med	13	Influence of the Internet of Things management system on hand hygiene compliance in an emergency intensive care unit Discusses impact of 2009 Hand guidelines audit to measure HHC rates. Studies application of an IOT management system to improve HHC rates. (although there is no difference in HAIss) Improvement needs to be made to improve quality of hand hygiene

Mind Map		
Setting	Issue/Problem	Population
- Hand Hygiene - Hand Washing - Hand Sanitization - Hand-Rub dispensers - Healthcare-Acquired Infections	- Nursing Unit Design - Sensor Placement - Sanitization Compliance Policies - Data Analysis Techniques	- Nurses - Doctors - Clinicians - Specialists - Healthcare providers - Clinical Settings