Assessment Of An Aggregate Electronic Monitoring System To Measure Hand Hygiene In A Hospital Setting

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DISSERTATION

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This thesis is dedicated to my loving parents, Ed and Kathy Limper, and my husband, Zachary Himelhoch, without whose unwavering support and encouragement I would not be here today.

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HML

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LIST OF ABBREVIATIONS

AHRQ	Agency for Healthcare Research and Quality
ABHR	Alcohol Based Hand Rub
APACHE	Acute Physiology and Chronic Health Evaluation
C. difficile	*Clostridium difficile*
CLABSI	Central Line Associated Blood Stream Infection
CTSA	Clinical and Translational Science Award program
EMR	Electronic Medical Record
EVS	Environmental Services
HH	Hand Hygiene
HAI	Healthcare Associated Infection
HCP	Healthcare Personnel
HHMT	Hand Hygiene Monitoring Technology
ICD	International Classification of Diseases
ICU	Intensive Care Unit
IRR	Incidence Rate Ratio
IT	Information Technology
MRSA	Methicillin-resistant *Staphylococcus aureus*
NIH	National Institutes of Health
TAM	Technology Acceptance Model
TPB	Theory of Planned Behavior

LIST OF ABBREVIATIONS (Continued)

UCM	University of Chicago Medicine
UTAUT	Unified Theory of Acceptance and Use of Technology
VRE	Vancomycin-resistant Enterococcus

SUMMARY

A number of hand hygiene monitoring technology (HHMT) options have become available on the commercial market, using technology such as Radiofrequency Identification (RFID) and Infrared Technology (IR) to measure both use of soap and alcohol-based hand rub (ABHR) as well as movement of healthcare personnel (HCP) throughout a hospital setting (Limper et al., 2016). Hand hygiene monitoring technology varies greatly in capability, reflecting an ever-growing technological market without clear evidence on the impact these systems have on hand hygiene (HH). Some systems report consumption of hand hygiene products, others provide HH compliance feedback without reminders, others provide real-time reminders without feedback, and some provide both individual feedback and real-time reminders (Boyce, 2008; Limper et al., 2016; Ward et al., 2014). Similarly, feedback may be provided at the hospital unit-level, room-level, or individual-level with reminders ranging from vibrating wearable devices to audible reminders that hands should be washed. While such technologies provide promise for more accurate measurement of hand hygiene compliance, questions surrounding the practicality and efficacy of these systems remain (Boyce, 2011; Pineles et al., 2014; Ward et al., 2014).

In addition to a need for assessment of the efficacy and effectiveness of HHMT, knowledge on the acceptance or rejection of such systems by healthcare personnel is similarly necessary (Boyce, 2011). We aimed to apply conceptual theories rooted in behavioral science to the assessment of perceived usefulness of HHMT. Finally, the ability to quantify the impact of HHMT coupled with real-time feedback of HH performance on clinical outcomes will close the loop on validation of the accuracy of HHMT, acceptance of the technology, and use of HHMT to quantify the impact of HH on the transmission of infection.

SUMMARY (Continued)

First, we aimed to assess the accuracy of an aggregate- level hand hygiene monitoring technology at measuring hand hygiene behavior in an inpatient hospital setting. Accuracy was quantified using sensitivity and positive predictive value calculations when compared to the gold standard approach to measuring hand hygiene, direct observation.

Second, we investigated the acceptability of an aggregate level HHMT for measuring HH behaviors among healthcare personnel. Rooted in the Theory of Planned Behavior (TPB) and the Technology Acceptance Model (TAM), we developed and administered a survey tool designed to quantify perceived usefulness and perceived ease of use of an aggregate-level hand hygiene monitoring technology.

Finally, we quantified the association of hand hygiene performance and incidence of healthcare-associated infections (HAI) including methicillin-resistant *Staphylococcus aureus*, *Clostridium difficile (C .diff)*, and vancomycin-resistant enterococci using a robust dataset including hand hygiene performance data collected 24 hours a day, 7 days a week, over a 19-month period.

I. INTRODUCTION

A. Background

Healthcare-associated infections (HAI) are associated with extraordinary cost, both in terms of patient outcomes and hospital expenses. Approximately 1.7 million patients acquired a HAI in 2002 alone, accounting for approximately 99,000 deaths (Klevins et al., 2007). The economic impact of these infections has been estimated at $6.5 billion each year (Stone et al., 2005).

Hand hygiene (HH) is widely believed to be the most effective modifiable factor for the prevention of HAIs (Whitby et al., 2007). Hand washing has been known to be a successful infection control strategy since it was first shown by Ignaz Semmelweis to reduce the incidence of puerperal fever in women during labor in 1847 (Boyce and Pittet, 2002). Since then, a large body of evidence has accumulated showing a temporal association between improved hand hygiene compliance and significant reduction in a plethora of healthcare-associated infections including overall HAI rates (Pittet et al., 2000), methicillin-resistant *Staphylococcus aureus* (MRSA) cross-contamination (Pittet et al., 2000), bacteremia (Grayson et al., 2008), and infection rates (Mestre et al., 2012), ventilator-associated pneumonia (VAP) (Al-Tawfig et al., 2013), central line-associated blood stream infection (CLA-BSI) (Al-Tawfig et al., 2013), and catheter-associated urinary tract infections (Al-Tawfig et al., 2013). While very little published evidence exists on the necessary threshold of HH compliance for effective prevention of infection, 2 clinical studies found lower incidence of MRSA, drug-resistant *Escherichia coli* and carbapenem-resistant *Pseudomonas aeruginosa* in hospital units achieving at least 70% compliance (WHO, 2014).

Despite the evidence supporting HH as an effective and cost-beneficial approach to infection prevention and control, HH rates remain alarmingly low at most US hospitals, with compliance averaging a mere 20% - 40% (Schneider et al., 2009; Boyce et al., 2009). Campaigns designed to improve hand hygiene have largely failed or produced benefits that have been limited in both scale and sustainability (Best and Neuhauser, 2004; Boyce et al., 2006; Whitby et al., 2007). Suboptimal interventions have included one-time educational interventions, feedback mechanisms, and administrative mandates. While these interventions have served to increase knowledge about hand hygiene, most have failed to produce long-term change in compliance (Best and Neuhauser, 2004). The most successful interventions have been those that incorporate a multimodal approach encompassing education, behavioral modification, and decreased barriers to performing HH (Buffet-Bataillon et al., 2010; O'Boyle et al., 2001). A systematic review of the literature conducted by the Cochrane Collaboration in 2010 deemed current assessments of the effectiveness of efforts intended to improve HH compliance inconclusive as a whole (Gould et al., 2010). The authors call for further research using more rigorous methodology and recommend development of interventions founded in theoretical frameworks from the behavioral and social sciences (Gould et al., 2010).

A primary barrier to development of more rigorous interventions to improve hand hygiene is the lack of a reliable method to measure hand hygiene performance. The gold standard for measuring HH performance, direct observation, involves the use of 'secret shoppers' covertly recording HCP behaviors. Direct observation is resource intensive and estimated to capture a mere 1.2%-3.5% of HH opportunities in the most rigorously applied situations (Fries et al., 2011). A reliable method to quantify adherence to hand hygiene recommendations would provide the opportunity to ask sophisticated questions about the factors driving healthcare personnel behavior and would offer a tool for testing interventions, providing valuable data that could quantify the risk of healthcare associated infections attributable to hand hygiene compliance failures.

B. <u>Conceptual Framework</u>

Social cognition factors can be very useful tools for understanding clinical behavior (Godin et al., 2008; Limper et al., 2013). The Theory of Planned Behavior (TPB) was conceptualized in order to understand motivation to perform behaviors that are not entirely volitional (Ajzen, 1991). The underying assumption of this framework declares an individual's intention to perform a behavior as both the immediate determinant and the single best predictor of that behavior (Ajzen, 1991; Limper et al., 2013). Intention to perform a behavior is directly influenced by 3 enabling variables: attitude (feelings or affective regard for the behavior), subjective norm (a person's global perception about whether perople important to him/her think the behavior is important), and perceived behavioral control (general perceptions about having sufficient control to perform the behavior) (Ajzen, 1991; Limper et al., 2013). The Theory of Planned Behavior has served as a conceptual framework for assessing motivation to perform hand hygiene among healthcare personnel (O'Boyle et al., 2001; Limper et al., 2013).

The Technology Acceptance Model (TAM) incorporates the Theory of Planned Behavior, as well as other social cognition factors, to create a framework around the acceptance of technology. The TAM postulates that the acceptance or rejection of technology is based on an individual's intentions to use the technology, which is influenced by 2 main constructs: 1) perceived usefulness- "the degree to which a person believes that using a particular system would enhance his or her job performance" and 2) perceived ease of use- "the degree to which a person believes that using a particular system would be free of effort" (Davis, 1989). Developed in 1989, TAM research has accounted for as much as 10% of the space allocated to Information Systems publications since its inception (Holden, 2010). Despite the relative simplicity of this theory, TAM has routinely accounted for 30% - 40% of technology acceptance (Holden, 2010). Given previous applications of the Theory of Planned Behavior to assessing motivation to perform hand hygiene in the healthcare setting, and incorporation of TPB into the TAM framework, the Technology Acceptance Model is an obvious choice for framing studies designed to understand motivations to use hand hygiene monitoring technologies.

C. The GOJO SMARTLINK™ technology

The GOJO SMARTLINK™ hand hygiene monitoring technology is comprised of 5 main components: activity counters, dispenser actuation counters, data receivers, a secure server, and a digital monitor. Activity counters are mounted near the doorway in each patient room. These devices are comprised of 2 "detection zones," invisible cones that monitor thermal infrared energy (heat). A room entry or exit is captured when a human body walks through both detection zones, displacing heat in the zone. Infrared energy has been applied in other settings and is highly reliable at detecting human presence. Incorporation of 2 zones within each activity counter allows for a level of internal validation that prevents a room entry or exit from being captured when 1) a person walking in the hallway passes by the doorway or 2) a person in the patient room walks near the doorway without exiting. Despite this internal validation, directionality of this basic technology does not allow for accurate differentiation of an entry vs. an exit but simply 'counts' room activity.

Dispenser actuation counters are inserted into all alcohol-based hand rub and soap dispensers. These counters are unique housing systems that sit inside of the dispensers, resulting in no visible indications of monitoring. Counting mechanisms have been deployed in hospitals throughout the country and have proven to be accurate in their ability to detect the number of times a dispenser is actuated (Helder et al., 2012).

Data receivers are installed throughout the hospital unit to capture both 'heartbeats' and data counts from each activity counter and dispenser. All data captured - each room entry, room exit, soap dispenser actuation, ABHR dispenser actuation - are time-stamped based on the minute and second the data is received by a receiver. A secure cloud-based server captures all data from the receivers and stores information at the device level. An online user-interface allows for secure login where all monitored data can be reviewed in tabular or graphical format. This allows for assessment of data by hospital building, hospital floor, hospital unit, and time.

Finally, a digital monitor is installed at the nurses' station of each hospital unit, displaying real-time compliance data. There is minimal lag time from time of activity to time of display on the digital monitor as the data is sent from each device, through a receiver, and onto the cloud-based server. This lag time is often within the range of a few minutes. Hand hygiene performance data can be displayed in a variety of formats, and is calculated in the following manner to reflect common requirements to perform hand hygiene upon entering and again upon exiting a patient room or patient care area:

$$\frac{\textbf{\# Soap dispenser actuations} + \textbf{\# ABHR dispenser actuations}}{\textbf{\# Room entries} + \textbf{\# Room exits}}$$

Data can be rolled up to a hospital floor or building level but cannot be accurately assessed at a level of granularity more detailed than the hospital unit. In order to obtain room-level compliance data, the system would require assigning each soap or ABHR dispenser to a single patient room. This would then only include HH performed at dispensers assigned to the room where activity occurred (entry or exit) in compliance percentages. In other words, if a healthcare worker washed their hands in the hallway and then walked into a patient room 2 doors down, the system would not link the HH event to the room entry. As such, this system is limited to calculating performance by simply adding all hand hygiene activity (dispenser activations) and all room activity (entries and exits) during a defined period of time to provide unit-level compliance.

Working with new technologies, or a new application of well-established technologies, does not come without unique challenges. While infrared technology is highly accurate at detecting human presence, it lacks the capability to detect directionality of movement. This means that in order to determine that a room activity is an “entry” or an “exit,” logic must be applied within the system; this logic exists within each activity counter. The order in which each zone is activated determines labeling of a room activity as an “entry” or an “exit.” A movement that triggers Zone 1 then Zone 2 results in an Entry while a movement that triggers Zone 2 than Zone 1 results in an Exit. When a person purposefully enters a patient room, this type of logic is highly accurate at assigning directionality of movement. However, it is anticipated that in daily practice, zones may be triggered out of order, resulting in mislabeling of room activity. For example, imagine a HCP inside of a patient room. A second HCP walking in the hallway leans into the doorway to communicate with the first HCP, triggering detection Zone 1, and then leaves. If the first HCP then exits the patient room quickly, this room activity will be labeled as an “Entry” when in reality it was an “Exit.” Since all hand hygiene compliance is reported at an aggregate unit level, without the ability to separate compliance upon entry vs. exit, we do not anticipate this technological limitation to be a limitation of the proposed study. It is worth reiterating that soap and ABHR dispensers are not assigned to specific patient rooms; this allows

HCPs to perform HH at any dispenser but prohibits calculation of HH compliance at the room level.

A second limitation of this technology is the process of time-stamping events at the moment the data reaches a data receiver. In general, this process allows for near real-time feedback of hand hygiene compliance, lagging by a few minutes of actual behavior. However, when validating the accuracy of this system against direct observation, an event may be time-stamped up to 5 minutes after the activity occurred. While this introduces complexity to the validation process, we are confident this limitation can be accounted for.

D. Purpose of the Study

The purpose of this research was to assess the accuracy and acceptance of a Hand Hygiene Monitoring Technology (HHMT) approach to measuring hand hygiene in an inpatient hospital setting. Additionally, this research aimed to use HHMT to quantify the impact of hand hygiene on incidence of healthcare-acquired infections. Our long-term goal is to establish new best practices for measuring hand hygiene performance in the healthcare setting. The current research represents 3 critical steps for that long-term goal. First, we aimed to assess the accuracy of an aggregate-level hand hygiene monitoring technology using direct observation to quantify the sensitivity and positive predictive value (PPV) in measuring hand hygiene behaviors. Second, we aimed to quantify acceptability of an aggregate level HHMT for measuring HH behaviors among healthcare personnel using a survey tool rooted in behavioral theory. Finally, we quantified the association of hand hygiene performance and incidence of healthcare-associated infections (HAI) including methicillin-resistant *Staphylococcus aureus*, *C. difficile*, and vancomycin-resistant enterococci using a robust dataset including hand hygiene performance data collected 24 hours a day, 7 days a week, over a 2-year period. These steps led to the following 3 study Aims:

1. To quantify the accuracy of an aggregate hand hygiene monitoring technology in measuring hand hygiene behavior of healthcare personnel in an inpatient hospital setting.

2. To investigate the acceptance of a hand hygiene monitoring technology among healthcare personnel.

3. To investigate the association of hand hygiene performance and incidence of healthcare-associated infections using hand hygiene monitoring technology to measure hand hygiene behavior.

E. <u>Significance of the Study</u>

A number of hand hygiene monitoring technology (HHMT) options have become available on the commercial market, using technology such as Radiofrequency Identification (RFID) and Infrared Technology (IR) to measure both use of soap and alcohol-based hand rub (ABHR) as well as movement of healthcare personnel throughout a clinical environment. Hand hygiene monitoring technology (HHMT) varies greatly in capability, reflecting an ever-growing technological market without clear evidence on the impact these systems have on hand hygiene. While such technologies provide promise for more accurate measurement of hand hygiene compliance, questions surrounding the practicality, efficacy, and cost-effectiveness of these systems remain (Ward et al., 2014; Boyce, 2011; Pineles et al., 2014).

A systematic review including 42 articles surrounding automated measuring systems found fewer than 20% of studies identified calculations for accuracy or efficacy of these systems

(Ward et al., 2014). Of these, the level of rigor for assessment of system accuracy was variable. Many facilities have installed HHMT based on manufacturer's assessments of accuracy, which are often inadequate and can differ greatly based on the physical space in which the system is deployed. Given the critical need to improve hand hygiene performance among healthcare personnel, along with increasing pressure from accreditation bodies to measure and improve hand hygiene (Joint Commission, 2015), a methodology is urgently needed to assess the efficacy of hand hygiene monitoring technology in a standardized way, to allow for comparison both with the gold standard – direct observation- and among each other (Limper et al., 2016). In order for HHMT to be useful to clinicians, the data it provides must be accurate. Hence, validation of hand hygiene monitoring technologies must be tested in actual clinical practice to avoid overestimation or underestimation of accuracy (Pineles et al., 2014).

While validation of emerging technologies is the first necessary step in assessing HHMT as an appropriate method for measuring hand hygiene, the ability to predict and explain acceptance of such technologies by healthcare personnel is equally vital. Currently, published literature on this topic is limited to the use of focus groups to qualitatively assess potential uptake of a single wearable technology after a brief simulation (Boscart et al., 2008). This study was not founded in any theoretical framework and was conducted by the inventors of the technology in question, leaving great room for improvement in such assessments. The Technology Acceptance Model (TAM) is an ideal framework for hand hygiene technologies given its foundational grounding in such theories as the Theory of Planned Behavior which has been successfully applied to understanding intentions to perform hand hygiene among healthcare personnel (O'Boyle et al., 2001; Limper et al., 2013). This Aim of purposeful assessment of end-user acceptance of HHMT is the logical next step in rigorous evaluation of measurement approaches for hand hygiene.

Finally, the availability of new methods to measure hand hygiene 24 hours a day, 7 days a week brings vast opportunity to associate HH performance with acquisition of pathogens in the hospital setting. For this objective, hand hygiene performance is treated as a predictor of acquisition of healthcare-associated infections. The ability to quantify this association using large amounts of hand hygiene data will further our knowledge around appropriate recommendations for hand hygiene performance as an effective means to prevent the spread of infection.

II. REVIEW OF RELATED HAND HYGIENE LITERATURE

A. The Burden of Healthcare Associated Infections

Healthcare-associated infections (HAI) are associated with extraordinary cost, both in terms of patient outcomes and hospital expenses. A single HAI can cost a hospital between $26,040 and $68,146 and such infections are estimated to cost a 200-bed facility more than $1.7 million per year (Pittet et al., 2000). In addition to these monetary costs, a patient with a healthcare-associated infection will spend, on average, an additional 2.61 days in the hospital (Erasmus et al., 2009). Trauma patients who acquire an infection while in the hospital environment have shown 1.5- to 1.9-fold higher odds of mortality and 3- to 4-fold higher length of stay compared to trauma patients without HAIs (Glance et al., 2011). Nearly half of healthcare-associated infections may result from inadequate hand hygiene by healthcare staff (Larson and Kretzer, 1995).

B. Hand Hygiene As An Effective Method for Infection Prevention

Hand hygiene (HH) is widely believed to be the most effective modifiable factor for the prevention of HAIs (Whitby et al., 2007). Hand washing has been known to be a successful infection control strategy since it was first shown by Ignaz Semmelweis to reduce the incidence of puerperal fever in women during labor in 1847 (Boyce and Pittet, 2002). Since then, a large body of evidence has accumulated showing a temporal association between improved hand hygiene compliance and significant reduction in a plethora of healthcare-associated infections including overall HAI rates (Pittet et al., 2000), methicillin-resistant *Staphylococcus aureus* (MRSA) cross-contamination (Pittet et al., 2000), bacteremia (Grayson et al., 2008), and infection rates (Mestre et al., 2012), ventilator-associated pneumonia (VAP) (Al-Tawfig et al., 2013), central line-associated blood stream infection (CLA-BSI) (Al-Tawfig et al., 2013), and catheter-associated urinary tract infections (Al-Tawfig et al., 2013). While very little published evidence exists on the necessary threshold of HH compliance for effective prevention of infection, 2 clinical studies found lower incidence of MRSA, drug-resistant *Escherichia coli* and carbapenem-resistant *Pseudomonas aeruginosa* in hospital units achieving at least 70% compliance (WHO, 2014). Despite the evidence supporting HH as an effective and cost-beneficial approach to infection prevention and control, HH rates remain alarmingly low at most US hospitals, with compliance averaging a mere 20% - 40% (Schneider et al., 2009; Boyce et al., 2009).

C. Approaches to Measuring Hand Hygiene Performance

In addition to complex factors at the individual and environmental levels, a fundamental challenge to improving hand hygiene performance among healthcare personnel (HCP) is the reliable measurement of adherence to these practices. An emerging approach to hand hygiene improvement is the adoption and testing of new methods for measuring HH performance. Presently, the gold standard for measuring HH compliance involves the use of trained observers periodically and covertly assessing healthcare personnel and recording their adherence with accepted HH standards (Boyce, 2011). These standards are often limited to compliance with performing HH upon entering and exiting a patient room, also known as 'wash in, wash out' policy. This is due in part to physical limitations to directly observing all recommended opportunities for HH but also because of the need to increase the amount of data captured through this resource intensive 'secret shopper' method. Direct observation is estimated to capture a mere 1.2%-3.5% of all hand hygiene opportunities (Fries et al., 2011). In addition, the Hawthorne effect has been well described with estimates of a 3-fold inflation in hand hygiene performance when auditors are present (Eckmanns et al., 2006; Srigley et al., 2014). Preliminary data from the University of Chicago quantifying this effect when using an unknown student observer, compared to a known Infection Preventionist, is shown in Table I. While this method is resource-intensive and generally too costly to apply on a large scale, alternative approaches have also been inadequate: self-reported behavior assessments are biased and surrogate markers such as measurement of hand gel consumption are unreliable (Haas and Larson, 2007; Boyce, 2008).

TABLE I. HH COMPLIANCE VARIATION BY DATA COLLECTOR

Unit	Unknown Student	Infection Preventionist
Unit A	27%	65%
Unit B	34%	65%
Unit C	16%	69%
Unit D	29%	70%

A reliable method to quantify adherence to hand hygiene recommendations would provide the opportunity to ask sophisticated questions about the factors driving HCP behavior and would offer a tool for testing interventions, providing valuable data that could quantify the risk of healthcare associated infection attributable to hand hygiene compliance failures. A number of hand hygiene monitoring technology (HHMT) options have become available on the commercial market, using technology such as Radiofrequency Identification (RFID) and Infrared Technology (IR) to measure both use of soap and alcohol-based hand rub (ABHR) as well as movement of healthcare personnel throughout a unit. Hand hygiene monitoring technology (HHMT) varies greatly in capability, reflecting an ever-growing technological market without clear evidence on the impact these systems have on hand hygiene. While such technologies provide promise for more accurate measurement of hand hygiene compliance, questions surrounding the practicality, efficacy, and cost-effectiveness of these systems remain (Ward et al., 2014; Boyce, 2011; Pineles et al., 2014).

D. Acceptance of Hand Hygiene Monitoring Technology

Hand hygiene monitoring technology provides an opportunity to continuously measure hand hygiene behaviors over time while mitigating behavioral biases associated with direct observation (Boyce, 2013). However, apart from limited published data on the validity of these technologies, little exists on perceptions, acceptance, and utilization of these systems by healthcare personnel in the United States (Boyce, 2013). Available data is limited to findings from focus groups assessing human factors components that may affect uptake of wearable technologies (Boscart et al., 2008). Moreso, these small studies have been conducted by product developers. There is a need for research assessing the acceptability of such systems to comprehensively assess the practicality of hand hygiene monitoring technoloy as an approach to measuring hand hygiene.

E. Using HHMT to Asses the Relationship Between Hand Hygiene and HAIs

Hospital-acquired infections (HAI) account for extraordinary cost and increased duration of hospitalization (Klevens et al., 2002). It has been estimated that 7% - 10% of hospitalized patients will acquire a HAI during their hospital stay (Smith et al., 2003). The most common pathogen reported to the National Healthcare Safety Network is *C. difficile,* causing 12.1% of healthcare-associated infections associated with 16.7% attributable mortality at 1 year (Magill et al., 2014; Dubberke et al., 2008). Nearly half a million infections were due to *C. difficile,* causing an estimated 29,000 deaths in 2011 alone (Lessa et al., 2015). Costs associated with *C. difficile* infections have been estimated between $6,000 and $9,000 per infection.

The second most common overall cause of HAIs reported to the National Healthcare Safety Network is methicillin-resistant *Staphylococcus aureus* (MRSA) (Jernigan and Kallen, 2010). Prevalence of MRSA infection is estimated to be 4% among hospitalized patients, approximately 35% of which is diagnosed more than 48 hours after admission, which is categorized as hospital-acquired (Abramson and Sexton, 1999; Cummings et al., 2010). MRSA infection is associated with increased length of stay and can result in severe sequelae such as bloodstream infections, pneumonia, and surgical wound infections. In addition to the clinical burden of MRSA, the average total hospital cost associated with a single episode of hospital-acquired MRSA infection (HA-MRSA) has been estimated at $50,000 (Cummings et al., 2010).

Complicating the impact of this antibiotic-resistant organism is the ability to carry MRSA asymptomatically (colonization). The Centers for Disease Control and Prevention estimate nearly 1 in 3 individuals carry *Staphylococcus aureus* in their nose asymptomatically, while 2 in 100 people are colonized specifically with MRSA. Routine, and often mandated, surveillance to identify patients colonized with MRSA is conducted upon patient admission at most hospitals across the U.S., often focusing on admissions to an intensive care unit (IUC) setting. This active surveillance influences enforcement of isolation precautions for colonized patients. Active surveillance and isolation precautions, which include hand hygiene performance, have shown substantial reduction in MRSA transmission and bacteremia in the ICU setting (Lucet et al., 2005; Huang et al., 2006).

Vancomycin-resistant *Enterococci* (VRE) is most commonly found in healthcare settings, causing serious complications such as bacteremia and severe sepsis (Edmond et al., 1996). Infection with VRE nearly doubles risk of mortality (RR: 2.3, CI: 1.2-4.1) and is increasingly difficult to treat as antibiotic resistance continues limit treatment options (Edmond et a., 1996; Reik et al., 2008). A single infection with VRE has been estimated to cost $12,800 as of 2000. (Weinstein, 2000).

Despite a large body of evidence supporting hand hygiene (HH) as the most effective modifiable factor for prevention of the spread of infection, this known association has prevented the conduct of randomized controlled trials on ethical grounds for decades, resulting in a body of observational, quasi-experimental, and simulation modeling approaches. While this collective body of evidence strongly supports the impact of hand hygiene on prevention of HAIs including MRSA, many infection control programs continue to struggle in their work to prioritize hand hygiene as a patient safety goal with calls for stronger evidence from remaining critics.

Nearly all research assessing the causality of hand hygiene in preventing infection has relied on direct observation to measure hand hygiene performance. While this method provides the greatest level of detail around hand hygiene, including duration of wash and compliance before and after glove use, great resources are required to obtain large amounts of representative data. These requirements have often limited studies associating hand hygiene trends with incidence of HAIs to small observational samples extrapolated to a larger population. The introduction of hand hygiene monitoring technology (HHMT) to the commercial market has ushered in a unique opportunity to investigate the impact of hand hygiene on HAI acquisition through the ability to compile thousands of data points every day. The ability to correlate trends in HH performance and incidence of HAIs over time using continuous monitoring of HH has the potential for great impact. The Aim of this initiative was to assess the relationship between hand hygiene performance and incidence of HAIs at a large academic medical center using hand hygiene monitoring technology.

III. METHODOLOGY

A. Study Sample

The University of Chicago Medicine (UCM) is a major teaching hospital located in Chicago, Illinois. It serves as the primary nexus of clinical care for the south side of Chicago and as the principal teaching hospital for the University of Chicago's Pritzker School of Medicine. With an inpatient capacity of over 600 beds, the health system sees more than 20,000 hospitalizations per year and almost 500,000 outpatient visits annually. The medical center provides a full spectrum of care from primary care through tertiary and quaternary care.

In addition to its clinical and teaching mission, the University of Chicago is also a major research center. With funding from the Agency for Healthcare Quality and Research (AHRQ), the National Institutes of Health (NIH), the Patient-Centered Outcomes Research Institute (PCORI), and many other sources, the University of Chicago has a vibrant, active research community that is also supported by an active Clinical and Translational Science Award (CTSA). These factors conspire to create an extraordinarily fertile ground for research; one that is embedded in an active and engaged clinical enterprise.

B. Data Collection

We collected, formatted, cleaned, and validated outcome and predictor variables using data captured in the electronic medical record (EMR), by the GOJO SMARTLINK™ hand hygiene monitoring technology, and through direct observation of healthcare provider behaviors. In addition, our team obtained access to sophisticated data warehouses that interface with the EMR. Queries and reports generated from these warehouses are very comprehensive and provide complete information at the individual data point level (e.g., specific lab results at a given point in time at a given hospital location). Data pertaining to healthcare personnel perceptions and acceptability towards HHMT were collected via a self-administered survey tool administered via paper and electronic modalities. RedCap, a secure web application for building and managing online survey tools, was used for electronic survey administration. RedCap is supported by federal funding (NIH CTSA UL1 TR000430).

C. Aim 1 Methodology

i. Preliminary work

Basic functionality of the aggregate electronic monitoring system throughout 3 hospital buildings found approximately 90% accuracy in the capability of the system to monitor purposeful human activity. This data, collected as part of ongoing quality control activities, is summarized in Table II. Percent accuracy was calculated by comparing the number of events detected by the HHMT to the number of events purposefully triggered. This preliminary data serves 2 important purposes: 1) piloting of the validation process and comparison of the HHMT to direct observation was assessed for feasibility in accomplishing Aim 1, below, and 2) basic functionality of the system was assessed to ensure feasibility of this project in its entirety.

ii. Approach

Hand hygiene compliance can be viewed and measured in a number of ways. One way to measure HH performance is an encounter-based approach, whereby compliance is assessed during an entire patient ‘encounter’ defined as the time period just before room entry to just after room exit. This requires observing hand hygiene performance upon room entry and again upon room exit, which may be a valuable approach for detection of patterns among healthcare workers. Another way to measure HH performance is an independent-event approach, treating each room entry and room exit as separate events which often maximizes efforts of an observer who is no longer required to observe HH performance upon room entry and again upon room exit of a healthcare worker. For the purposes of accuracy assessment, we used an independent-event approach to allow for real-time identification of inaccuracies at the device level. This initiative was deemed quality improvement and not human subjects research and was therefore not reviewed by the Institutional Review Board.

TABLE II. PRELIMINARY DATA TO ASSESS FEASIBILITY OF SYSTEM TO DETECT PURPOSEFUL HUMAN BEHAVIOR BY INVESTIGATORS

Unit	Room Entry	Room Exit	Soap Dispenser	ABHR Dispenser
A	100%	96.4%	97.3%	96.6%
B	91.7%	91.7%	100%	96.3%
C	90.0%	100%	100%	100%
D	92.9%	93.1%	92%	93.1%
E	92.3%	92.0%	100%	100%
F	91.7%	91.7%	100%	100%
G	91.7%	91.7%	92.9%	97.0%
H	100%	94.7%	100%	100%
I	90.9%	100%	100%	100%
J	92.9%	92.9%	92.5%	96.6%
K	96.3%	92.3%	92.3%	90.0%
L	100%	90.0%	97.2%	91.1%
M	92.0%	90.9%	97.1%	98.1%
N	90.9%	90.0%	93.3%	100%
O	90.1%	92.3%	93.3%	95.0%
P	90.6%	91.2%	94.9%	94.4%

iii. Calibration and structural assessment

Hand hygiene monitoring technology requires significant investment of resources into proper calibration and should not be expected to work as "plug and play" technology. Structural variation between hospitals and hospital units are likely to impact the efficacy of systems, particularly those monitoring room entry and exit. For instance, our preliminary validation found the following components to affect accuracy of capturing room entries/exits: distance of room activity counter from the floor under a room doorway, presence and width of "breakaway" doors that may block entry/exit sensors, and distance of activity counters from room curtains. Additionally, ensuring the structural soundness of installed technology to remain on a wall or ceiling during routine clinical activity is vital to both the accuracy of the system and initial buy-in from hospital staff.

Once "face validity" of the system was deemed acceptable, a high-level data assessment was conducted to ensure proper function of the installed technology. For example, an intensive care unit is likely to record a higher number of hand hygiene opportunities than a patient floor. Next, basic functionality of the system was tested using a *planned path*.

iv. Planned path

A planned path is simply a route created throughout a unit or hospital area that allows for systematic validation of a hand hygiene monitoring technology through purposeful activation of each activity counter and hand hygiene dispenser (Figure 1). A planned path was developed for each hospital unit, accounting for every soap dispenser, ABHR dispenser, and every monitored room, as seen in Figure 1. Completion of the entire planned path was accompanied by documentation of deviations that occurred due to patient care, as well as any activity presumed to interfere with documentation of the planned path. For example: if upon entry into a patient room by the planned path investigator, a healthcare provider entered the same room, which should trigger 2 ‘room entry’ events by the HHMT rather than the intended one ‘room entry’ from the planned path, this was documented. Detailed notes were essential to allow for comparison of performed behavior with activity captured by the HHMT.

Soon after the planned path was completed, data was pulled from the HHMT and compared to each device encounter. Devices that failed the planned path were adjusted and again assessed using the planned path approach. This cycle was repeated until all devices were functioning properly. We set a “passing threshold” of 100% for this test. In other words, each device had to correctly “pick up” the planned path activity at least once before proceeding to the next step. Once this was accomplished, real-world accuracy was tested using *behavioral validation.*

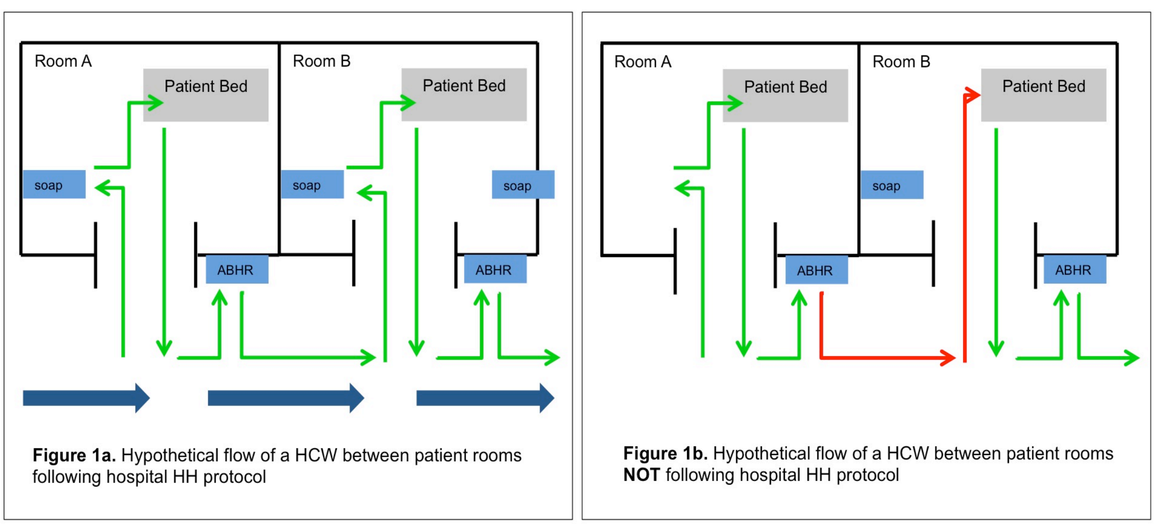


Figure 1a. Hypothetical flow of a HCW between patient rooms following hospital HH protocol

Figure 1b. Hypothetical flow of a HCW between patient rooms **NOT** following hospital HH protocol

Figure 1. Comparison of planned path and natural healthcare worker behavior

v. Behavioral validation

Unlike the *planned path* approach, which is designed to quantify a system's accuracy in detecting purposeful behavior of system investigators, *behavioral validation* quantifies a system's ability to accurately detect real-world behaviors in the hospital or clinic environment. As seen in Figure 1, flow of healthcare personnel throughout the hospital environment is often chaotic and non-predictable. Behavioral validation requires trained observers to document all activity in and out of patient rooms as well as all soap and ABHR dispenser actuations. Similar to the planned path approach, observers documented unusual behaviors due to patient care and any behaviors that may pose difficulty for the system. For instance, many HHMTs available today struggle to accurately account for multiple room entries that occur simultaneously. Thus, when groups of individuals entered or exited a patient room together, this was clearly documented in order to validate the system's accuracy in accounting for these activities. Additionally, based on preliminary validation, the following observations were noted: lingering in doorways, accompaniment of a mobile computer or large machine when entering or exiting a patient room, and opening/closing of room doors.

A small set of rooms were observed for at least 30 minutes at a time (often for multiple hours) to ensure all activity in and out of rooms was observed and recorded. During both calibration and planned path approaches, soap and ABHR dispensers, which use simple mechanical counting mechanisms to record actuations, were adjusted until 100% accuracy was reached for each device. As such, behavioral validation was restricted to room activity, which is technologically more complicated to accurately document.

vi. Sample size

While *planned path* was conducted until each dispenser reached 100% accuracy, a sample size was calculated for measuring sensitivity of the system during *behavioral validation.* Sample size calculation for sensitivity as the primary diagnostic measure of interest has been recommended as (Hajian-Tilaki):

$$\mathbf{n_{Se} = \frac{Z^2_{x/2}\hat{S}e(1 - \hat{S}e)}{d^2 \times Prevalence}}$$

An alpha of 0.05 equated to $Z_{X/2} = 1.96$, while sensitivity was conservatively set at 80% based on preliminary observations. The precision or maximum marginal error was set at 10% and prevalence was set at 50%. While prevalence of hand hygiene performance was known to range from 20% to 40%, the prevalence for the sample size calculation was an estimate of the proportion of behavior that was related to hand hygiene – entering into a room, exiting a patient room, or actuating a dispenser- out of all person movement on the hospital unit. In other words, it was estimated that 50% of movement on the unit was either in the hallway or patient room. This is a conservative estimate based on routine observation of provider behavior, specifically focused on walking throughout the unit. Plugging in these values, the sample size calculation used was:

$$\mathbf{n = \frac{(1.96^2)(0.8)(0.2)}{(0.1^2)(0.5)} = 123}$$

Traditional observation averages 15 observations per hour using infection preventionists at the University of Chicago Medicine, placing the estimated time needed to observe 123 events around 8.2 hours. Given the unique microsystem of each hospital unit, observers aimed to collect 123 observations on each of the 24 inpatient hospital units across 3 hospital buildings, requiring an estimated 197 hours of observation.

To account for known limitations of the HHMT in applying timestamps to events, which may delayed up to 3-5 minutes from when the event took place if a unit experiences high volumes of activity, observations were conducted in 30-minute time blocks, adding 5 minutes before and after the 20-minute period of interest. This allowed for detection of events that may have experienced a time stamp delay. Activities for this Aim received a formal Determination of Quality Improvement status according to University of Chicago Medicine institutional policy. As such, this initiative was deemed not human subjects research and was therefore not reviewed by the Institutional Review Board.

vii. Outcome definitions (dependent variables)

The primary outcomes of interest for this Aim were: 1) sensitivity of the technology – the ability to capture events that occurred and 2) positive predictive value (PPV) of the technology – the probability that events captured by the system actually occurred (Figure 2). An event was defined as 1) actuation of a soap dispenser, 2) actuation of an alcohol-based hand rub dispenser, 3) entry into a patient room, or 4) exit from a patient room.

	Observed (Direct Obs)	Not Observed (Direct Obs)	
Counted (HHMT)	True Positive (TP)	False Positive (FP)	**PPV** =TP/(TP+FP)
Not Counted (HHMT)	False Negative (FN)	True Negative (TN) *	
	Sensitivity = TP/(TP+FN)		

Figure 2. Sensitivity and positive predictive value calculations

Traditionally, calculations of sensitivity are complimented by measures of specificity- the proportion of true negatives among all detected negative results (true non-events and false negatives). However, it is not possible to determine the true number of non-events (non-dispenser actuation, non-room activity), prohibiting the ability to calculate an accurate measure of specificity. Thus, accuracy assessments were limited to sensitivity and PPV analysis. Sensitivity was calculated as:

$$\frac{\textbf{\# of events captured by HHMT and direct observation}}{\textbf{\# of events captured by direct observation}}$$

Positive predictive value (PPV) was calculated as:

$$\frac{\textbf{\# of events captured by HHMT and direct observation}}{\textbf{\# of events captured by HHMT}}$$

Finally, hand hygiene performance – defined as the proportion of room entries and room exits accompanied by a HH event (dispensing of soap or ABHR) – was measured using the aggregate HHMT system. This calculation was assessed at the most granular level available using the HHMT, the hospital unit, and was calculated as:

$$\frac{\textbf{\# soap dispenser actuations + \# ABHR dispenser actuations}}{\textbf{\# room entries + \# room events}}$$

viii. Predictor definitions (independent variables)

For this Aim, predictor variables were data elements considered potentially interfere with system accuracy such as structural attributes of a physical space and volume of unit activity. It was hypothesized that units experiencing higher volumes of room entries and exits would have lower system accuracy compared to units experiencing lower volumes of room activity. In general, the Intensive Care Units (ICUs) experience higher volumes of room activity throughout the day when compared to inpatient floors. Thus, sensitivity of the system was stratified to look at differences, if any, between ICUs and inpatient floors as well as across 3 unique hospital buildings. The effect of unit microsystems was also assessed by calculating outcomes for each distinct hospital unit.

ix. Potential confounders

The infrared (heat) technology used by the aggregate-level hand hygiene monitoring technology deployed uses heat displacement to count room activity. One of the known limitations of this system is the inability to differentiate whether a person walking in or out of a patient room or performing hand hygiene is a healthcare personnel or patient visitor. Thus, the primary confounding variable of interest when assessing the accuracy of this HHMT was proportion of visitor activity. While healthcare providers may define unit 'visitors' as any person not routinely assigned to a unit, visitors were defined as non-hospital workers (i.e. patients, patient families, or patient visitors) for the purpose of this Aim. Since hand hygiene policies apply to all healthcare personnel, regardless of assigned or floating status, the intention of this confounding variable was to account for contributions to the hand hygiene compliance denominator – room entries and exits- that were attributed to patients and their visitors.

x. Analysis strategy

Data collected via direct observation was considered the 'source of truth' and compared to data captured electronically by the HHMT. Following the extreme independent-based approach noted above, each device encounter was considered a unique event, allowing for separate validation of room entries, room exits, soap dispenser actuations, and ABHR dispenser actuations. Data collected by the HHMT was pulled in its most raw format and included: date of event, time of event, type of event (i.e., soap dispense, ABHR dispense, room entry, room exit), and location of event. In addition to these variables, data recorded via direct observation included attribution of room activity to a healthcare worker or visitor as well as any relevant notes for each event.

Sensitivity, the probability that true activity will be captured by the system, was calculated separately for planned path and behavioral validation. Similarly, positive predictive value, the probability that activity captured by the system really occurred, was calculated for both planned path and behavioral validation. This allowed for assessment of system efficacy – accuracy during purposeful activity conducted during the planned path phase – and effectiveness – accuracy during real-world activity documented during behavioral validation. These fundamental epidemiologic measures were then stratified by estimated proportion of visitors and physical location. Analysis was conducted using Excel 2011 and Stata/SE 13.1 for Mac (Stata Corporation, College Station, Texas).

xi. Alternative approaches

A number of alternative approaches could be used for this Aim. For example, while video surveillance monitoring could be used to validate dispenser actuations in addition to room activity, the placement of the video cameras at our institution did not allow for visualization of many dispensers, making this approach infeasible. Similarly, video surveillance could be an alternative approach to quantifying the proportion of room activities attributable to hospital visitors. However, a very small proportion of room doorways are visible through video surveillance, at our institution, prohibiting acquisition of a representative sample of true room activity.

D. Aim 2 Methodology

i. Preliminary work

"Voice of the Customer" is a Lean Management tool used much like a structured interview. A series of 4 open-ended questions were developed: 1) Your electronically monitored hand hygiene rate for the month is XX%. What do you think of that?; 2) What would make this information more or less believable to you?; 3) What do you think contributes to the hand hygiene rate of your unit?; and 4) If you were in charge, what would you do to improve the hand hygiene rate? In June 2014, a total of 25 healthcare personnel working on 2 inpatient hospital units piloting the GOJO SMARTLINK™ technology were interviewed to inform operational leaders regarding perceptions of hand hygiene and performance measurement using the new technology. Further employing Lean Management tools, answers to each of these questions were recorded, transcribed, and analyzed using an affinity diagram (Table III). This approach, conducted by a team of 10 organizational leaders, categorized responses thematically in order to summarize the rich qualitative feedback collected from frontline staff. Thematic responses to this exercise included: a) a perception that low collective hand hygiene performance is attributable to others, not oneself; b) a lack of prioritization of HH among other daily tasks; c) lack of trust in the ability of the technology to accurately measure hand hygiene; and d) calls for education and accountability to improve hand hygiene compliance across the medical center.

TABLE III. AFFINITY DIAGRAM FROM STRUCTURED INTERVIEWS

Affinity Summary

Affinity Group	**Number of Responses Containing Theme** South	West	Both Units Combined	**Larger Affinity Group**	
Think current # is low/bad	7	11	**18**		
Other Staff *(sum of MDs specifically and any other)*	**14**	**20**	**34**	57	It's not me, it's you
Other Staff - MDs	*8*	*9*	*17*		
Other Staff (any other than me personally or my discipline)	*6*	*11*	*17*		
Patient, family, visitors	**10**	**13**	**23**		
Forget	3	2	5	18	Spectrum of forget, no time, urgent/emergent
Urgency	1	3	4		
Not enough time	4	5	9		
GoJo User Interface	1		1		
Don't Understand GoJo	**8**	11	**19**		
Don't believe #s (are right or accurate)	2	8	10		
Believe the #s	6	**13**	**19**		
Standards unclear	1	2	3		
Dispenser/HH equipment Issues	7	3	10		
But I'm not touching anything...	**9**	8	17	24	System counts against us when it shouldn't (perception)
Washed on way out, don't need to again on way in	1	2	3		
Empty Rooms	1	1	2		
Other count against when it shouldn't	2		2		
Reminders *(including POC, signs, and verbal)*	**8**	8	16		How to improve
Education	5	**12**	17		
Accountability		7	7		
Make it a competition	3		3		
Offer rewards	2	1	3		
Provide data	5	7	12		
Provide data by discipline		4	4		

ii. Approach

a. Survey development

The Technology Acceptance Model (TAM) postulates that the acceptance or rejection of technology is based on one's intentions to use the technology, which is influenced by 2 main constructs: 1) perceived usefulness- "the degree to which a person believes that using a particular system would enhance his or her job performance" and 2) perceived ease of use- "the degree to which a person believes that using a particular system would be free of effort" (Davis, 1989). Developed in 1989, TAM research has accounted for as much as 10% of the space allocated to Information Systems publications since its inception (Holden, 2010) and has routinely accounted for 30% - 40% of technology acceptance (Holden, 2010). Rooted in this social cognition theory, a survey tool was designed to quantify healthcare provider perceptions of the aggregate-level GOJO SMARTLINK™ hand hygiene monitoring technology.

Complementing the TAM framework, preliminary findings from Voice of the Customer exercises were integrated into the survey tool. For example, questions measuring perceived accuracy of the system and attitudes regarding aggregate-level, or collective, hand hygiene performance were incorporated into the tool. The survey was comprised of 26 questions and a free text area for additional comments. Demographic and participant descriptor variables included job role, gender, ownership of a smartphone, frequency of working in clinical areas, hospital unit most frequently assigned to, presence of the HHMT on hospital unit most frequently assigned to, and familiarity with the HHMT. The majority of questions were asked on a 4-point Likert-type scale measuring level of agreement (i.e. Strongly Do Not Agree, Do Not Agree, Agree, Strongly Agree) or level of frequency (i.e. Never, Occasionally, Sometimes, Always). Questions were collaboratively developed by a team with expertise in hand hygiene measurement, the GOJO SMARTLINK^{TM} technology in particular, adaptation of the TAM framework, and survey design theory.

b. Study design

Prior to widespread rollout, the survey tool was administered to a small group of 13 healthcare personnel with varying levels of both clinical experience and familiarity with the implemented GOJO SMARTLINK^{TM} technology. Results were reviewed with this pilot cohort in order to identify areas for improvement of face validity and overall clarity of the tool. Changes to the survey tool were limited to word choice and grammatical improvements. This group identified an average time of 4-minutes required to complete the survey.

Participants were recruited using electronic mailing listservs, in-person recruitment at staff meetings, and approved advertisement methodologies across the University of Chicago Medicine (UCM) campus during March 2016 - April 2016. All faculty and staff associated with the medical center were eligible to participate with a desire to focus on clinical healthcare personnel. The survey was administered in both electronic and paper-based formats, tailored to individual needs of participants with varying degrees of access to the electronic modality. All data was entered and managed using RedCap (Research Electronic Data Capture) tools hosted at the University of Chicago. Redcap is a secure, web-based application designed to support data capture for research studies, providing: 1) an intuitive interface for validated data entry; 2) audit trails for tracking data manipulation and export procedures; 3) automated export procedures for seamless data downloads to common statistical packages; and 4) procedures for importing data from external sources. All paper-based surveys were entered into RedCap by a single investigator. This study was approved by the Institutional Review Boards at the University of Chicago and University of Illinois at Chicago.

iii. Outcome definitions (dependent variables)

Aligning with the Technology Acceptance Model, the primary outcomes of interest were *perceived usefulness* and *perceived ease of use* of the hand hygiene monitoring technology. Together, these outcomes were intended to best predict attitudes towards the GOJO SMARTLINK^{TM} technology that influence behavioral intention to use the technology.

Perceived usefulness is defined as the "degree to which a person believes that a particular system would enhance his or her performance outcomes (Holden and Karsh, 2010), in this case the outcome being hand hygiene. This composite variable incorporated 6 survey questions, displayed in Table IV, each measured on the scale "Strongly Disagree, Disagree, Agree, Strongly Agree" coded as 0-3. The construct 'perceived usefulness' was created in an additive manner, creating a composite scale, 0 – 18, with higher scores representing greater perception of usefulness of the hand hygiene monitoring technology.

TABLE IV. COMPOSITE VARIABLE 'PERCEIVED USEFULNESS'

Perceived usefulness
I find the HHMT useful in my job
The HHMT is useful for understanding HH performance
I believe the HHMT is a good approach to measuring HH
I believe the HHMT is a good approach to improving HH
The HHMT promotes hand hygiene as a priority
I believe the HHMT accurately measures HH behaviors

Perceived ease of use is defined as the "degree to which a person believes that using a particular system would be free of effort" (Davis, 1989). This composite variable also incorporated 5 survey questions, displayed in Table V, each measured on the scale "Strongly Disagree, Disagree, Agree, Strongly Agree" coded as 0-3. Prior to creating the composite variable 'perceived ease of use,' the responses to negatively constructed questions, ("I sometimes find it difficult to use the HHMT;" "I sometimes find my interaction with the HHMT to be unclear;" and "I sometimes find the HHMT hard to understand"), were reversed in order to create a unidirectional composite variable. The construct 'perceived ease of use' was then created in an additive manner, creating a composite scale, 0 – 15, with higher scores representing greater perceived ease of use of the HHMT.

TABLE V. COMPOSITE VARIABLE 'PERCEIVED EASE OF USE'

Perceived ease of use
I understand how my interaction with the HHMT impacts HH performance
I find it easy to get information from the HHMT
I sometimes find it difficult to use the HHMT[1]
I sometimes find my interaction with the HHMT to be unclear[1]
I sometimes find the HHMT hard to understand[1]

[1]Order of variable responses were reversed prior to creating composite variable

While perceived usefulness and perceived ease of use were the primary outcomes of interest, self-reported use of the HHMT was also measured as a marker of actual system use. This composite variable incorporated 3 survey questions, displayed in Table VI, each measured on a positively constructed scale coded as 0-3. The construct 'self-reported system use' was created in an additive manner, creating a composite scale ranging 0 – 9, with higher scores representing greater interaction and use of the HHMT. Following the TAM, both perceived usefulness and perceived ease of use were anticipated to predict self-reported use of the technology.

TABLE VI. COMPOSITE VARIABLE SELF-REPORTED USE OF HHMT

Self-reported system use
I pay attention to the lights on activity counters
I look at HH performance on the monitor
I use the HHMT to track HH behavior

iv. Predictor definitions (independent variables)

Each survey question was analyzed for its relationship with both primary outcomes perceived usefulness and perceived ease of use. The exploratory nature of this survey, for which no current data exists, supported an in-depth assessment of all potential relationships in the data. However, the primary predictor of interest for both outcomes was an individual's attitude towards aggregate-level, or collective, hand hygiene performance. It was hypothesized that a strong belief in the benefits of hand hygiene would predict strong perceptions of ease of use and usefulness of a system designed to measure hand hygiene behaviors. Furthermore, since the HHMT in question can only measure HH behaviors at the unit level, it was hypothesized that a strong belief in the benefits of participation in collective HH behaviors would predict stronger perceptions around perceived ease of use and usefulness of an aggregate-level HHMT.

The following questions were posed to measure involvement in collective hand hygiene and attitude towards group HH: 1) I discuss HH performance at staff huddles, 2) I remind others to perform HH, 3) I am reminded to perform HH by others, and 4) I believe I can contribute to hand hygiene performance. The first 3 questions were measured on the scale “Never, Sometimes, Occasionally, Always,” coded as 0-3, while belief in ability to contribute was measured on the scale “Strongly Disagree, Disagree, Agree, Strongly Agree,” also coded as 0-3. It should be noted that a hospital-wide campaign to promote discussion of HH at daily huddles was well established at the time of survey administration, supporting the relevancy of this metric.

v. Potential confounders

Potential confounders of both primary outcomes included frequency of work in clinical areas and familiarity with other technologies. Participants were asked, “How often do you work in clinical areas?” (Never, Occasionally, Sometimes, Always), “Do you own a smartphone,” and “How often do you use apps?” to measure each of these variables. Additionally, the questions “Which best describes your experience with hand hygiene monitoring technology?” (Not At All Familiar, Not Very Familiar, Somewhat Familiar, Very Familiar) and job role were measured as potential indicators of opportunity to interact with the HHMT. Finally, gender has been seen to significantly influence attitudes towards hand hygiene, particularly around the association between HH and skin health, and was thus included as a potential confounder (Limper et al., 2013).

vi. Analysis strategy

First, frequencies of responses to each survey question were tabulated to identify patterns, normality, and skewness to ensure a foundational understanding of the data. Next, a correlation matrix was constructed to include each composite variable as well as job role, gender, ownership of a smartphone, frequency of app use, frequency of clinical duties, familiarity with HHMT, belief in the ability to contribute to collective HH, and perceived accuracy of the HHMT. Relationships between each pair of variables were explored for both magnitude and direction. Participants indicating they were not aware of the technology (2.2%) were excluded from further analysis.

Each construct, “perceived usefulness,” “perceived ease of use,” and “self-reported system use,” was assessed for interrelatedness among the set of questions comprising each composite variable using a Chronbach’s alpha. Responses to negative questions such as “I sometimes find my interaction with the HHMT to be unclear” were reversed to create uni-dimensional constructs. Higher values indicate greater perceived usefulness, greater perceived ease in using the HHMT, increased system use, and greater involvement in collective hand hygiene through discussion and reminding techniques.

Both perceived ease of use and perceived usefulness were treated as continuous variables. This approach is commonly used for ordered categorical variables with at least 5 categories when it cannot be confidently assumed that the distance between categories is equal across the measurement scale. Unadjusted linear regression models were used to quantify crude associations between each potential predictor variable and perceived usefulness and perceived ease of use, separately. Using Stata/SE 13.1 for Mac, the xi command was used to generate dummy variables for categorical predictors in order to assess trends in variable relationship to the outcome of interest. For example, the predictor variable “frequency of clinical responsibilities,” originally structured as 0-3 corresponding to (Never, Occasionally, Sometimes, Always), was heavily skewed towards “Always” and determined to be most appropriately assessed as a dichotomous variable comparing Always to Sometimes/Occasionally/Never.

Stepwise backward-selection estimation using a conservative 0.10 p-value threshold was used to identify statistically significant predictors for each outcome. Next, results from unadjusted linear regression models and the correlation matrix were used to incorporate conceptually plausible predictors, confounders, and interaction terms into the multivariate linear regression model. Goodness of fit for each model was assessed using R-squared to quantify the proportion of outcome variation explained, overall significance of the model as measured by the F-test, and individual variable significance and magnitude of effect on the outcome of interest. Analysis was conducted using Excel 2011 and Stata/SE 13.1 for Mac (Stata Corporation, College Station, Texas).

vii. Alternative approaches

A number of alternative survey design approaches would have been appropriate. The Technology Assessment Model could have been moderately adapted to the topic of HHMT in an attempt to maintain the previously validated survey content. However, this modification would likely require re-validation of the survey tool and assessment that the intended constructs were being captured. Initial assessment of this approach found only moderate modification to result in an unclear application of previously validated questions to the content at hand. As such, the decision to use preliminary data collected via structured interviews, combined with expert opinion, was deemed a more appropriate approach to ensure development of a tool truly tailored to measure acceptance of HHMT.

Similarly, ordinal logistic regression analysis could have been conducted given the ordinal nature of the outcomes perceived usefulness and perceived ease of use. As a sensitivity analysis, ordinal logistic regression was conducted and compared to linear regression models. Interpretation of crude associations between all potential predictors and each composite outcome were synonymous in both direction and statistical significance for ordinal and linear regression approaches. Given the large range of each outcome variable (0-15) as well as the inability to confidently assume the proportional hazards assumption holds, linear regression analysis was chosen as the most appropriate methodology for this study.

E. <u>Aim 3 Methodology</u>

Our 600-bed academic medical center installed the GOJO SMARTLINK™ hand hygiene monitoring system throughout the month of July 2014 across all adult and pediatric inpatient settings. Combining dispenser actuation counting devices and infrared technology, this HHMT provides hand hygiene compliance data at the hospital unit-level 24 hours a day, 7 days a week.

The medical center conducts active surveillance of MRSA colonization upon admission to an intensive care unit (ICU), independent of source of admission (i.e. admitted through the emergency department or transferred from an inpatient floor), triggering isolation precautions as necessary. Outside of the ICU setting, passive surveillance of MRSA colonization is conducted at clinician discretion. All screening for MRSA colonization is performed using nasal swab and polymerase chain reaction (PCR) testing. Independent of screening for MRSA colonization, physicians suspecting infection or high risk of infection with MRSA order laboratory cultures for diagnosis. All positive MRSA cultures receive a flag in the electronic medical record (EMR) prompting the treating physician to place the infected patient on isolation precautions. This flag does not distinguish site or invasiveness of infection but rather is a dichotomous indicator of infection presence accompanying laboratory test results.

Data was collected, formatted, cleaned, and validated using sophisticated data warehouses that interface with the EMR. Queries and reports generated from these warehouses are very comprehensive and provide information at the individual data point level (e.g., a specific lab result at a given point in time at a given hospital location). All metrics, routinely collected for quality improvement purposes, were pulled for this analysis between August 1, 2014 and February 29, 2016. This initiative was deemed to be quality improvement by the University of Chicago Medicine and therefore was not reviewed by the Institutional Review Board according to institutional policy.

i. Cohort assembly

All flags in the electronic medical record indicating a positive MRSA culture associated with an inpatient hospital admission were pulled between August 1, 2014 and February 29, 2016 (Figure 3). During a single encounter, a patient may develop MRSA infection in multiple body sites, triggering multiple flags. Therefore, the first flag indicating a positive MRSA culture was kept and any subsequent flags were removed, creating a dataset of 172 unique patient admissions with a positive MRSA culture. The unit of observation was the patient encounter and included the following variables: date of hospital admission, colonization status of the patient, order date of the MRSA culture test, unit from which the order for MRSA culture was placed, time to MRSA acquisition, patient Charlson Comorbidity Index, and patient demographics including age, gender, and race. Time to MRSA acquisition was defined as the number of hours between time of hospital admission and time the order was placed for an MRSA culture test.

The Charlson Comorbidity Index is a standardized scale measuring underlying risk of mortality by categorizing comorbidities of patients based on International Classification of Diseases (ICD) diagnosis codes. A total of 17 comorbidities are weighted on a scale of 1 to 6 based on adjusted risk of associated mortality (Charlson et al., 1987; Deyo et al., 1992; Quan et al., 2005). Higher scores indicate greater comorbidity and thus greater risk of morbidity over a 1-year period. Comorbidities included are: myocardial infarction, congestive heart failure, peripheral vascular disease, cerebrovascular disease, dementia, chronic pulmonary disease, rheumatic disease, peptic ulcer disease, mild liver disease, diabetes without chronic complication, diabetes with chronic complication, hemiplegia or paraplegia, renal disease, any malignancy, moderate or severe liver disease, metastatic solid tumor and HIV/AIDS (Charlson et al., 1987; Deyo et al., 1992; Quan et al., 2005).

Hand hygiene data collected via the HHMT technology was available at a level of granularity no more detailed than the hospital unit level. Therefore, this hospital encounter-level dataset was rolled up to monthly data, stratified by unit. In total, there were 19 months during the period under investigation and 29 hospital units, creating a dataset with 551 observations at the monthly level, by unit. This cohort included both adult and pediatric inpatients cared for across 3 hospital buildings.

In parallel to this MRSA infected cohort, a separate data pull identified 9,360 nasal swab tests for MRSA colonization during the August 2014 – February 2016 time period. All duplicative swabs occurring within a single patient encounter were removed, leaving 7,395 unique patient encounters with the first nasal swab colonization test and result. The unit of observation was the patient encounter and included the following variables: date of hospital admission, colonization status of the patient, order date of the nasal swab, unit from which the order for the nasal swab was placed, and patient demographics including age, gender, and race.

Again accounting for the level of granularity of hand hygiene data, this hospital encounter-level dataset was rolled up to monthly data, stratified by unit. In total, there were 19 months during the period under investigation and 29 hospital units, creating a dataset with 551 observations at the monthly level, by unit. This cohort included both adult and pediatric inpatients cared for across 3 hospital buildings.

These 2 datasets, comprised of the first MRSA nasal swab indicating colonization status and the first positive MRSA culture, were joined into the final dataset used for analysis. Keeping the unit of observation as month, stratified by unit, hospital operational data was integrated into the dataset including: # of hand hygiene events (the total # of soap and ABHR dispenser actuations), # of hand hygiene opportunities (the total # of patient room entries and exits), monthly HH rate (# HH events / # HH opportunities), and daily census at 6am. By taking the sum of each daily census on a unit, this variable provided the total number of patient-days. Hand hygiene data was available for 28 of the 29 hospital units with patient encounter-level data, which left 532 observations in the final dataset. Since the HHMT was installed over time throughout the medical center, observations at the unit/month level were removed for months without the hand hygiene monitoring technology. This left 334 observations in the final dataset. The cohort assembly process is depicted in Figure 3.

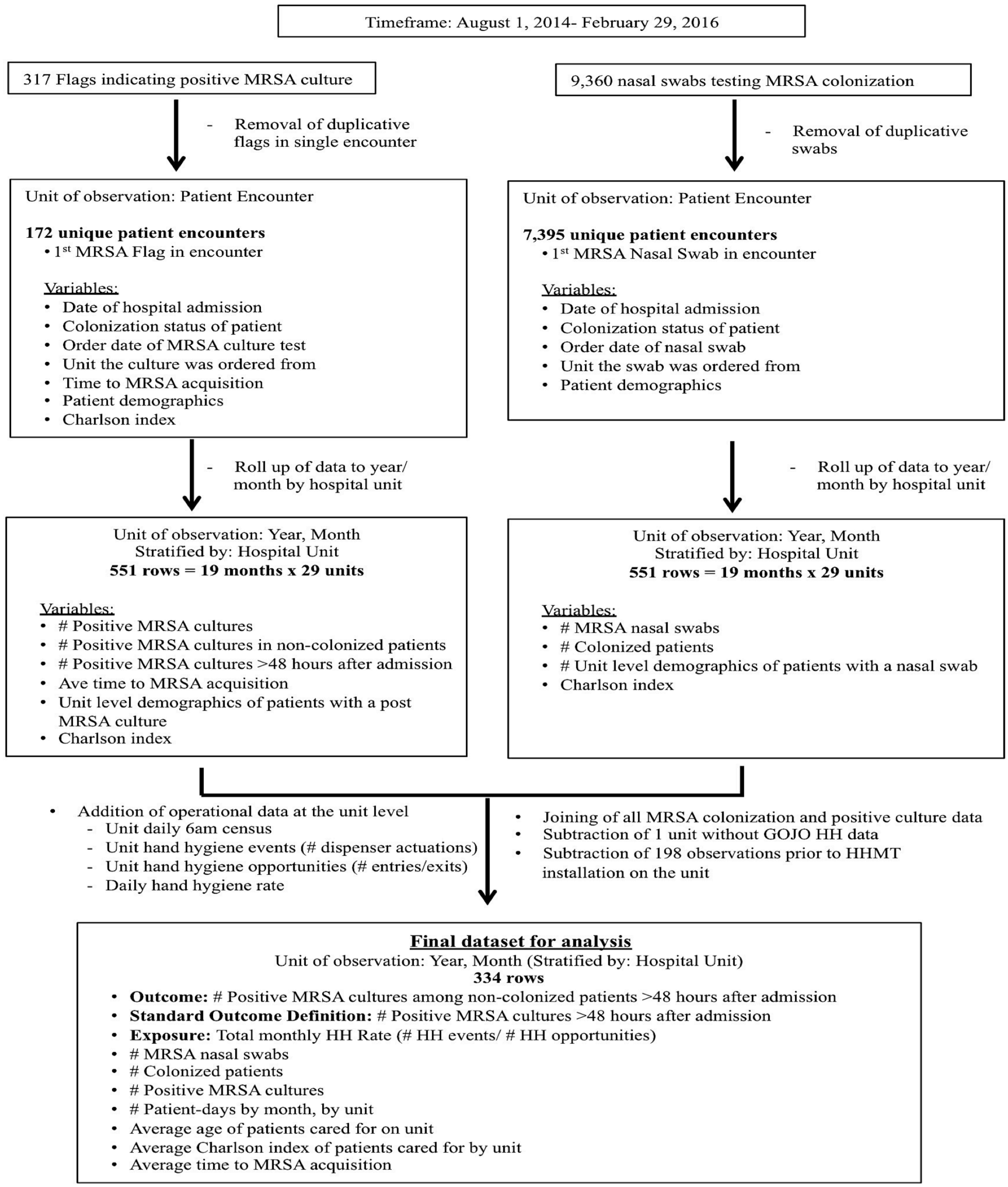


Figure 3. Cohort assembly process

Using similar flags, the number of positive *C. difficile* infections diagnosed greater than 48 hours after admission and number of positive vancomycin-resistant Enterococcus (VRE) diagnosed greater than 48 hours after admission were added into this dataset. *C. difficile* is diagnosed using PCR testing while VRE diagnosis is based on positive culture.

ii. Outcome definitions (dependent variables)

Standard definitions among hospitals attribute infections identified in a patient greater than 48 hours after hospital admission to incidence of hospital-acquired infection. Therefore, for each of the 3 organisms of interest – MRSA, *C. difficile*, and VRE – hospital acquisition was defined as having a positive diagnostic test greater than 48 hours after hospital admission. Specifically, hospital acquisition for each organism was defined as:

HA-MRSA: a positive MRSA culture that was ordered >48 hours after admission

HA-*C. difficile*: a positive *C. difficile* PCR test that was ordered >48 hours after admission

HA-VRE: a positive VRE culture that was ordered >48 hours after admission

HAI: acquisition of MRSA, *C. difficile*, or VRE with an order placed >48 hours after admission

Each hospital stay was treated as an independent event with unique risk for acquisition of infection. This allowed for classification of MRSA infections by colonization status during the same inpatient stay, distinguishing MRSA infection among patients who entered the hospital as carriers from infection among patients non-colonized at the time of admission. This active surveillance for MRSA colonization among inpatients allowed for a more robust definition of hospital acquired MRSA as ***a positive MRSA culture >48 hours after admission in an individual identified as non-colonized using nasal swab and PCR testing.*** While swabs to determine colonization status may be ordered across the medical center, active surveillance is limited to intensive care units. Thus, this outcome metric heavily represents patients cared for in the ICU setting rather than the broader inpatient population. Given the aggregated nature of hand hygiene data and the dataset in question, each outcome was calculated in terms of incidence:

$$\frac{\textbf{\# of positive diagnostic tests per month}}{\textbf{\# of patient days per month}}$$

In summary, 4 outcomes were assessed in this analysis: 1) incidence of hospital-acquired MRSA using the standard definition, 2) incidence of hospital-acquired MRSA among non-colonized individuals, 3) incidence of hospital-acquired *C. difficile*, and 4) incidence of hospital-acquired VRE.

iii. Predictor variables (independent variables)

In July 2014, the GOJO SMARTLINK$^{\text{RM}}$ hand hygiene monitoring technology (HHMT) was installed across inpatient units throughout the medical center. Combining dispenser actuation counting devices and infrared technology, this HHMT provided hand hygiene compliance data defined as:

$$\frac{\textbf{\# soap dispenser actuations + \# ABHR dispenser actuations (i.e. HH events)}}{\textbf{\# room entries + \# room events (i.e. HH opportunities)}}$$

at a level of granularity no more specific than the hospital unit-level. Despite the aggregate form of this measurement approach, HH performance measured 24 hours a day, 7 days a week, over the course of 19 months was collected for this initiative (August 1, 2014 – February 29, 2016). This performance data was compiled into monthly HH events and monthly HH opportunities at the hospital-unit level. HH rate was therefore expressed as:

$$\frac{\textbf{\# HH events per month}}{\textbf{\# HH opportunities per month}} \times 100$$

iv. Potential confounders

A number of variables have been postulated as contributors to increased risk of infection acquisition at the individual level including underlying comorbidities, length of stay, sex, race, and age. The Charlson Comorbidity Index was used to measure underlying comorbidities and age at discharge was incorporated. Patient-reported gender, rather than biological sex, was captured in the EMR. Biological plausibility was not supportive of a relationship between gender identity and risk for HAI acquisition, thus gender was not included in analysis. Similarly, race is often incorporated into such analyses to account for underlying factors contributing to patient health and risk for infection. The Charlson Comorbidity Index was deemed a more appropriate marker for underlying disease and race was therefore not included in analysis.

Complimenting patient-level characteristics that may confound the relationship between hand hygiene performance and acquisition of infection, the number of patients being cared for at a given point in time who are colonized with MRSA increases the risk of MRSA acquisition among other patients being treated at that same point in time. Thus, for assessment of the outcome MRSA acquisition, the number of patients colonized with MRSA was treated as a potential confounding factor. Finally, the number of visitors has been seen to influence the positive predictive value of the GOJO SMARTLINK™ hand hygiene monitoring technology

(Aim 1). The proportion of visitors was integrated into this analysis using dummy variables to represent the quartiles of this measure (0-13.2%, 13.3-17.6%, 17.7%-20.5%, 20.6%-41.7%).

v. Analysis Strategy

Monthly frequencies for each of the outcomes by hospital unit were very low, prohibiting enough power to explore the relationship of interest. Therefore, the relationship between each outcome and hand hygiene rate was assessed across the entire medical center over the 19-month period. Across the 19 months of analysis, no known changes occurred in methodologies for MRSA screening, MRSA diagnosis, *C. difficile* diagnosis, VRE diagnosis, nor measurement of hand hygiene.

Count data is often analyzed using Poisson regression approaches to account for the positive skew associated with a concentration of values equal to zero. This distribution assumes the mean and variance of the count variable to be equal. Testing this assumption, the difference in mean and variance for each outcome was calculated across the population, when HH rates were less than 50%, and when HH rates were greater than or equal to 50% (Table VII). MRSA acquisition, defined both by the standard definition and when restricted to non-colonized patients, met this criteria (Table VII). The difference between mean and variance counts of *C. difficile* was similarly minimal. VRE count data showed the greatest deviation from this assumption, although the difference between mean and variance in this outcome was not large. Further analysis revealed very low incidence of VRE diagnoses >48 hours after admission, making power an issue to truly assess the impact of hand hygiene rates on VRE acquisition. This may explain the higher inequality between mean and variance for this outcome compared to the other organisms. Analysis was conducted using Excel 2011 and Stata/SE 13.1 for Mac (Stata

Corporation, College Station, Texas) with a p-value less than 0.05 deemed statistically significant.

TABLE VII. ASSUMPTION OF EQUAL MEAN AND VARIANCE

	Unadjusted outcome			**HH Rate<median**			**HH Rate≥median**		
	Mean	Var	Abs(Diff)	Mean	Var	Abs(Diff)	Mean	Var	Abs(Diff)
MRSA >48hrs	0.715	0.583	0.132	0.781	0.596	0.185	0.630	0.561	0.069
MRSA in non-colonized	0.248	0.294	0.046	0.295	0.392	0.097	0.182	0.152	0.030
C. difficile >48 hrs	1.183	0.945	0.238	1.336	1.174	0.162	1.018	0.654	0.364
VRE >48 hrs	1.359	2.078	0.719	1.474	2.173	0.699	1.359	1.846	0.487

Each count variable was divided by patient-days per month to generate incidence of acquisition per 10,000 patient-days. To account for Poisson regression’s fit for count data, incidence rates were rounded to the nearest whole number. A generalize linear model specifying Poisson family, log link, and creating a scale to quantify the deviation of the outcome was used to quantify the effect of hand hygiene rate (# of HH events/# of HH opportunities x 100) on incidence of infection, separately for each outcome. Post-estimation commands were used to generate a prediction of the outcome based on this model. Next, this predicted incidence based on the effect of hand hygiene performance was subtracted from overall incidence, generating a new outcome variable representing the incidence of infection not explained by HH performance. The potential confounding variables average age, average Charlson Comorbidity Index of patients treated, month, and proportion of visitors were then treated as predictors of the incidence not explained by hand hygiene performance. Since the intention is to predict expected incidence based on HH performance when controlling for confounding factors, the right hand side of these equations were merged, combining intercept terms, to create the final predictive model quantifying the effect of HH performance on incidence of hospital-acquired infection.

vi. Alternative approaches

A number of alternative approaches could have been applied to this dataset. The use of logistic regression could have been used to predict the dichotomous variable of hospital-acquired infection for each organism. However, preliminary exploration of this approach displayed poor fit of the logistic regression model, likely due to the frequency of non-events in the outcome variables. Furthermore, the ability to collect hand hygiene data at the patient-room level would have made this analytic approach more desirable. If incidence of infection was highly prevalent and a linear relationship with HH identified, linear regression could have been used to assess the relationship of interest. Finally, if the relationship between hand hygiene performance and acquisition of infection were dependent on time, a time-series approach could have been applied. However, the investigators did not hypothesize that the relationship between hand hygiene and risk for infection was dependent upon the variable time, despite the known autocorrelation of hand hygiene. Specifically, HH rates exhibited autocorrelation with a lag of 4 days, reflecting the dependency of current HH performance on a unit on HH performance during the past 4 days on that unit. The aggregation of data to monthly rates is likely to account for this autocorrelation.

Both the format of count data and the rarity of each outcome made Poisson regression the most appropriate analytic method to assessing the relationship between hand hygiene performance and hospital-acquired infection. Zero-inflated Poisson regression is an analytic approach applied to count data with an excess of zero counts for which it is hypothesized that excess zeros are generated by process distinct from the count variables of interest. This approach allows for modeling of excess zeros independent from the Poisson count model. Preliminary exploration of this approach did not identify significant prediction of excess zeros. Additionally, investigators did not hypothesize a distinct risk to explain excess zeros but rather truly rare outcome events. Thus, Poisson regression was implemented for assessment of the relationship between number of healthcare-acquired infections per 1,000 patient days and hand hygiene performance.

IV. RESULTS AND DISCUSSION

A. Aim 1 Results

Data was collected by persons trained in direct observation using a standardized protocol to record behaviors related to hand hygiene over a 20-month period between 2014 - 2016.

i. Planned path

During the *planned path* phase, system investigators purposefully performed 4,872 unique events across 3 distinct hospital buildings varying in size and age since construction. Overall sensitivity across the medical center was 88.7% with a positive predictive value of 99.2%. System sensitivity was significantly variable across buildings ($p<0.001$) and was seen to be higher in newer Buildings A (92.6%) and C (93.3%) compared to an older Building B (85.2%). This trend held when sensitivity was stratified by event type- entry, exit, ABHR dispenser actuation and soap dispenser actuation (Table VIII). While overall positive predictive value did not significantly vary across buildings, stratification across event type found variation in PPV for both room entries ($p=0.046$) and room exits ($p=0.019$) when compared among the 3 hospitals (Table VIII). It should be noted that while room entry and exit were assessed as distinct events, the system's ability to distinguish an entry 'count' from an 'exit count' was found to be insufficient.

TABLE VIII. PLANNED PATH PLANNED ACCURACY BY BUILDING AND EVENT TYPE

	Total	**Building A**	**Building B**	**Building C**	**p-value**
Sensitivity	**88.7%**	**92.6%**	**85.2%**	**93.3%**	**<0.001**
Entry	89.4	90.6	88.5	90.6	0.558
Exit	86.1	86.7	84.2	92.4	0.030
ABHR	88.7	95.4	84.7	92.4	<0.001
Soap	91.5	94.4	82.9	98.2	<0.001
PPV	**99.2%**	**99.0%**	**99.5%**	**98.7%**	**0.062**
Entry	98.5	98.1	99.3	96.6	0.046
Exit	98.2	96.5	97.3	99.2	0.019
ABHR	99.8	100.0	99.7	100.0	0.314
Soap	100.0	100.0	100.0	100.0	--

Overall sensitivity and PPV, displayed in Table IX, were both seen to vary within buildings, across units. Of particular interest, units facing the southwest direction, which is only applicable to Building B, were seen to have lower rates of sensitivity than comparable units (Table IX). It is hypothesized that sunlight intensity may interfere with the ability of the HHMT to detect changes in heat necessary to 'count' room activity. While results are displayed for all planned path activity conducted, the HHMT devices were adjusted until each unit achieved at least 1 planned path with every device reaching 100% sensitivity on a single activation. These adjustments achieved 100% sensitivity and PPV on both soap and ABHR dispensers. Thus, behavioral validation was limited to room activity, which is far more difficult for HHMT to capture accurately.

TABLE IX. PLANNED PATH ACCURACY BY BUILDING AND HOSPITAL UNIT

	Sensitivity	PPV	N
Building A	**92.6%**	**99.0%**	**1,565**
Unit 1	97.4	100.0	151
Unit 2	88.6	100.0	158
Unit 3	95.6	100.0	69
Unit 4	89.4	98.6	162
Unit 5	97.2	100.0	144
Unit 6	94.2	100.0	155
Unit 7	96.7	96.2	191
Unit 8	89.2	97.4	217
Unit 9	90.3	100.0	124
Unit 10	94.8	100.0	58
Unit 11	89.0	100.0	136
Building B	**85.2%**	**99.5%**	**2,518**
Unit 12	90.7	100.0	237
*Unit 13	85.5	100.0	228
Unit 14	95.3	95.3	170
Unit 15	86.3	98.7	273
Unit 16	93.2	100.0	234
*Unit 17	63.5	100.0	219
Unit 18	92.0	100.0	225
Unit 19	90.6	100.0	361
Unit 20	87.6	100.0	340
*Unit 21	77.9	100.0	231
Building C	**93.3%**	**98.7%**	**789**
Unit 22	92.9	98.6	227
Unit 23	91.9	98.8	261
Unit 24	95.0	99.0	301

ii. Behavioral validation

During the *behavioral validation* phase, trained direct observers recorded 5,539 unique events across 3 distinct hospital buildings (Table X). Overall sensitivity across the medical center was 92.7% and positive predictive value was 84.4%. System sensitivity remained significantly variable across buildings ($p=0.023$) and was again seen to be higher in newer Buildings A (94.2%) and C (92.5%) compared to an older Building B (91.7%). Overall positive predictive value also varied significantly across buildings ($p<0.001$). System sensitivity was slightly higher on inpatient floors ($p=0.031$) while PPV was significantly higher on intensive care unit (ICU) floors ($p<0.001$) (Table XI). Time of day, dichotomized as morning (12am-11:59am) or evening (12pm-11:59pm) did not have a significant impact on HHMT sensitivity ($p=0.167$), however PPV was higher during morning hours ($p<0.001$) (Table XI).

The most frequently documented events that resulted in false positive HH opportunities included hovering of persons near the doorway, a series of quick room entries and exits, and room activity accompanied by a mobile computer or piece of medical equipment (e.g. ultrasound machine). Another notable finding during *behavioral validation* was the impact of HCP workflows on the performance denominator. Placement of medical supplies outside of the patient room required nursing staff to frequently enter and exit rooms while carrying supplies. There were 34 entries or exits accompanied by a machine and 100% of these were counted as 2 entries/exits by the HHMT. Similarly, terminal cleaning of recently vacated rooms was seen to require an estimated 10 room entries and exits on average, per room. This artificially penalizes HH performance rates for units with greater volumes of discharged patients.

TABLE X. BEHAVIORAL VALIDATION ACCURACY
BY BUILDING AND HOSPITAL UNIT

	Sensitivity	**PPV**	**N**	**Visitor activity**
Building A	**94.2%**	**89.7%**	**1,681**	**11.5% (121/1056)**
Unit 1	98.1	83.5	123	11.1 (4/36)
Unit 2	93.9	93.9	141	13.3 (8/60)
Unit 3	94.9	92.9	148	8.2 (12/146)
Unit 4	96.1	97.0	105	9.9 (7/71)
Unit 5	82.6	96.5	137	20.3 (27/133)
Unit 6	96.5	89.3	253	16.0 (38/237)
Unit 7	89.3	97.1	153	1.8 (1/56)
Unit 8	91.5	93.1	63	13.6 (6/44)
Unit 9	100.0	73.5	234	13.5 (8/59)
Unit 10	93.2	95.7	198	4.0 (8/199)
Unit 11	100.0	88.1	126	13.3 (2/15)
Building B	**91.7%**	**81.7%**	**2,447**	**22.0% (129/593)**
Unit 12	92.0	81.7	270	20.0 (10/50)
Unit 13	95.5	88.0	199	18.7 (14/75)
Unit 14	94.1	82.7	243	4.0 (2/50)
Unit 15	96.3	78.3	275	18.2 (10/55)
Unit 16	94.1	78.7	232	41.7 (25/60)
Unit 17	86.7	69.1	240	21.9 (14/64)
Unit 18	90.8	86.3	223	17.6 (9/51)
Unit 19	89.5	89.0	287	21.7 (13/60)
Unit 20	87.3	82.4	178	23.2 (20/86)
Unit 21	90.7	80.9	300	28.6 (12/42)
Building C	**92.5%**	**82.7%**	**1,411**	**15.5% (62/399)**
Unit 22	80.2	92.9	139	3.3 (3/60)
Unit 23	96.0	78.6	749	20.5 (40/195)
Unit 24	91.5	86.4	523	13.2 (19/144)

TABLE XI. BEHAVIORAL VALIDATION ACCURACY BY BUILDING, FLOOR TYPE, AND TIME OF DAY

	Sensitivity	p-value	PPV	p-value[1]
Floor type		p = 0.031		p < 0.001
ICU	91.0%		93.2%	
Floor	92.9%		82.6%	
Building		p= 0.023		p < 0.001
A	94.2%		89.7%	
B	91.7%		81.7%	
C	92.5%		82.7%	
Time of day		p = 0.167		p < 0.001
AM	92.8%		87.0%	
PM	91.7%		81.5%	
Proportion of Visitors		p < 0.001		p < 0.001
0 – 13.2%	91.3%		89.7%	
13.3% - 17.6%	95.4%		85.7%	
17.7% - 20.5%	93.9%		81.5%	
20.6% - 41.7%	89.8%		80.3%	

[1]Note: p-values are associated with student's t-test and ANOVA as appropriate

The main confounding factor considered in this analysis was the proportion of room activity contributed by patients and families, collectively referred to as visitors. It should be noted, this proportion does not reflect the proportion of visitors compared to HCP but the proportion of room activity attributed to patients and their visitors. Visitors were observed frequently hovering in doorways to signal attention of healthcare personnel and moving throughout the patient room near doorways. These behaviors may explain findings that the proportion of visitor activity significantly affected system sensitivity ($p<0.001$) and positive predictive value ($p<0.001$) (Table XI). Proportion of visitor activity ranged from 1.8% to 41.7% of all room entry and exit activity. Quartiles were defined as 0-13.2% (33% of units), 13.3% - 17.6% (18% of units), 17.7% - 20.5% (28% of units), and 20.6% - 41.7% (21% of units). When the proportion of visitor activity was categorized into quartiles, an inverse dose-response relationship between visitor activity and HHMT positive predictive value was seen. In other words, as the proportion of patient room entries and exits contributed by visitors increased, the probability that room activity captured by the HHMT was a true event decreased. Absolute percentage decrease in PPV was -4% comparing quartile 2 to quartile 1, -4.2% comparing quartile 3 to quartile 2, and -1.2% comparing quartile 4 to quartile 3.

The validation process followed installation of the GOJO SMARTLINK™ hand hygiene monitoring technology throughout all inpatient units, which occurred during July 2014 – June 2015. Since initiation of installation, hand hygiene performance across the inpatient hospital areas has followed an upward trend (Figure 4). Calculated after installation across the medical center beginning in July 2015, total actuations of soap and ABHR dispenses/ total room entries and exits across the medical center, hand hygiene performance rose from 32.7% in July 2015 to 42.2% compliance in February 2016, a 9.5% crude increase. Similarly, total number of hand hygiene events – use of soap or ABHR – rose from 547,022 events in July 2015 to 1,222,681 events in February 2016, which was a 1.24% relative increase. Quality improvement efforts occurred across the medical center throughout this time with the intention of improving HH performance.

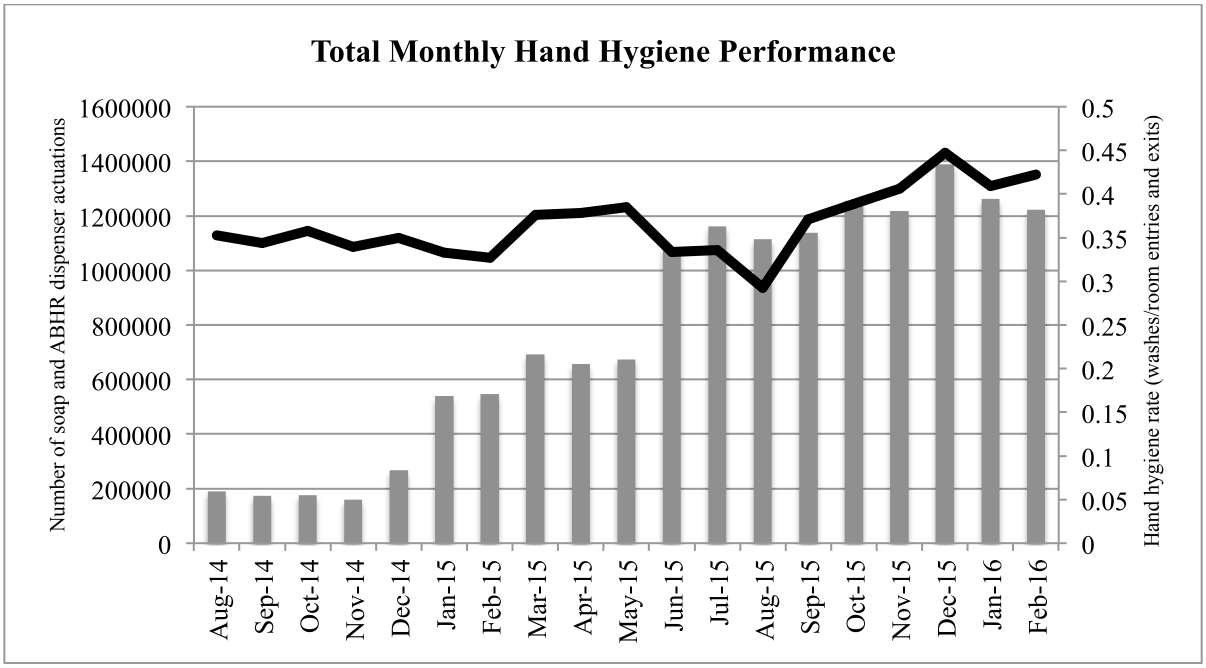


Figure 4. Hand hygiene performance and total dispenser actuations across inpatient areas

iii. Discussion

Overall efficacy of the hand hygiene monitoring technology, as measured by *planned path* validation, was high, quantified by an overall sensitivity of 88.7% and positive predictive value of 99.2%. Assessment of each room entry, room exit, soap dispenser actuation, and ABHR dispenser actuation allowed for targeted readjustment of devices that lead to 100% sensitivity and 100% PPV for hand hygiene events (soap and ABHR dispenser actuations). This allowed for assessment of system effectiveness by focusing on measuring the sensitivity and PPV for capturing hand hygiene opportunities (room activity). From a technological standpoint, this approach is valid. The ability to accurately measure soap or ABHR dispenser actuations relies solely on a mechanical counter placed in the dispenser. However, the ability to detect heat displacement at a level of accuracy that distinguishes room entry from nearby activity is technologically more complex. Thus, this narrowed scope during *behavioral validation* was justified.

Effectiveness of the HHMT, as measured by *behavioral validation,* was similarly high with overall system sensitivity increasing to 92.7% while PPV was 84.4%. This decrease in probability that a captured event actually occurred, when compared to the *planned path* phase, is likely due to the exclusion of soap and ABHR dispensers, which as stated above, reached 100% accuracy through targeted troubleshooting of dispensers. When tested in a natural healthcare environment, the system was highly likely to detect room activity, reflected by high sensitivity. However, the frequency of false positive events when measuring room activity is noteworthy – 15.6% of all hand hygiene opportunities were false positives. These false positive events result in a deflated hand hygiene rate as the denominator of HH compliance is artificially inflated.

Reduced positive predictive value of the system in capturing room activity was associated with behaviors and workflows that resulted in frequent activity in or near room doorways. This has significant impact on interpretation of hand hygiene performance for healthcare providers working on units with high proportion of visitor activities. Lower positive predictive value of the system to detect room entries and exits means these units have an inflated denominator in reported hand hygiene performance. In other words, HH performance is underestimated by 10%-20% depending on the proportion of room activity attributed to visitors (Table XI). Ideally, HH performance presented to HCP on these units should be adjusted to reflect this underestimation, increasing reported compliance by 10% - 20%, depending on visitor activity. Similarly, expectations for target HH performance should be adjusted to account for this underestimation of compliance in order to improve the usefulness of this metric to healthcare personnel. Efforts to reduce visitor hovering in doorways by encouraging call systems may also have a significant impact on reported HH performance, particularly on units with a high proportion of room activity contributed to visitors. Similarly, changes in HCP workflows to reduce room entries and exits, such as terminal cleaning of empty rooms and storage of supplies outside of patient rooms, may allow for more accurate measurement of true hand hygiene performance. However, this raises new questions concerning the necessity of performing HH upon every room entry and room exit and the definition of HH compliance based on a “wash in/wash out” policy. Further exploration of the need to perform HH upon room entry into an empty room or after carrying supplies may be helpful in further defining compliance in an era of HHMT.

iv. Conclusions

Objective measures of sensitivity and positive predictive value provide promise of the benefit of this and other hand hygiene monitoring technologies to capture basic behaviors associated with hand hygiene. The findings of this validation process support previous recommendations that accuracy of HHMT should be assessed in each unique physical location given the variation in accuracy detected between buildings, unit type (ICU vs. floor), and proportion of visitor activity (Limper et al., 2016).

Perhaps the most notable finding of this initiative was the significant impact of healthcare personnel workflows and visitor behaviors on system accuracy and thus HH performance. Further technological development is necessary to accurately account for necessary workflows such as transportation of medical equipment in and out of patient rooms, group activity during patient rounding, and visitor presence within patient rooms. However, efforts to redesign workflows around room cleaning, supply storage, and provider communication are likely also necessary to accurately measure hand hygiene performance using an aggregate level HHMT.

While adjustment of performance rates to account for system inaccuracies is necessary to accurately inform healthcare personnel, utility exists in continuous surveillance to visualize trends in performance, regardless of known underestimation.

With the advent of HHMT, questions regarding traditional "wash in/wash out" hand hygiene polices are likely to be challenged. Further development of technologies capable of distinguishing behavior near patient rooms or within empty patient rooms may provide a unique opportunity to quantify the risk associated with HH non-compliance across organic hospital workflows to further inform hospital hand hygiene policies.

B. Aim 2 Results

i. Survey results

A total of 259 healthcare personnel responded to the survey, resulting in a 6.4% response rate under the approximation that nearly 4,000 clinical staff are employed by the medical center. This convenience sample was obtained through recruitment at operational meetings, advertisement using medical center listservs, and intranet announcements. Additionally, investigators recruited participants via in-person rounding on hospital units, spending 1 hour per inpatient unit administering the paper-based survey tool during the course of 1 week including weekends. All healthcare personnel were eligible to participate. Paper-based surveys accounted for 46% of responses. Participants were comprised of 47.9% nurses and 21.2% physicians with 85% of respondents indicating frequent clinical responsibilities (Always/Sometimes) (Table XII). The majority of participants were female (80%), owned smart phones (95.8%), were very familiar with GOJO SMARTLINK™ (61.4%), and reported the unit to which they were most frequently assigned had installed the HHMT (80.7%).

TABLE XII. DEMOGRAPHIC CHARACTERISTICS OF STUDY POPULATION

Characteristic	Number	Percent
Job Role		
Nursing Staff	124	47.9
Physician or Physician Trainee	55	21.2
Other	63	24.3
Missing	17	6.6
Gender		
Female	208	80.3
Male	49	18.9
Missing	2	0.8
Clinical Duties		
Always	185	71.4
Sometimes	34	13.1
Occasionally	25	9.7
Never	12	4.6
Missing	3	1.2
Owns a smartphone		
Yes	248	95.8
No	7	2.7
Missing	4	1.5
GOJO is installed in my primary unit		
Yes	209	80.7
No	7	2.7
I don’t know	33	12.7
Missing	10	3.9
Primary building assigned to		
A	75	29.0
B	65	25.1
C	52	20.1
Float	33	12.7
Outpatient	3	1.2
Missing	31	12.0
Familiar with HHMT		
Very Familiar	159	61.4
Somewhat Familiar	75	29.0
Not Very Familiar	17	6.6
Not At All Familiar	6	2.3
Missing	2	0.8

It should be noted that the HHMT was present in all inpatient clinical areas, making this variable an indication of participant awareness. Among the 26 survey questions, 17 were measured on the scales "Strongly Do Not Agree, Do Not Agree, Agree, Strongly Agree" or "Never, Occasionally, Sometimes, Always." For these questions, frequencies of responses are displayed in Table XIII.

In general, participants did not agree the HHMT accurately measures HH, generally did understand how their interaction with the technology impacts HH performance, and frequently reported reminding others to perform HH (Table XIII).

To further explore relationships among variables collected, correlations were explored, revealing moderate correlation between familiarity with the HHMT and being a nurse (r: 0.31) (Table XIV). This finding likely aligns with the structure of an academic hospital where nurses are more frequently unit-based while physicians and ancillary healthcare personnel float across physical areas. Increased agreement that "I can contribute to improving HH performance" was correlated with perceived accuracy (r: 0.19), perceived usefulness (r: 0.27), self- reported system use (r: 0.21) and involvement in collective hand hygiene ($p= 0.15$). Notably, the outcome metrics perceived usefulness and perceived ease of use were correlated (r: 0.46), which is expected as these constructs work together to influence intention to use a technology according to the Technology Assessment Model.

TABLE XIII. FREQUENCY TABLE OF SURVEY RESPONSES, PERCENTAGES

Variable	n	Strongly Do Not Agree	Do Not Agree	Agree	Strongly Agree
I find the HHMT useful in my job	243	11.9	34.2	44.4	9.5
The HHMT is useful for understanding HH performance	238	7.1	28.2	53.8	10.9
The HHMT accurately measures HH performance	240	20.8	38.8	32.1	8.3
I believe the HHMT is a good approach to **measuring** HH	239	12.1	29.7	47.7	10.5
I believe the HHMT is a good approach to **improving** HH	239	8.0	21.3	59.0	11.7
The HHMT promotes hand hygiene as a priority	242	5.4	16.5	61.2	16.9
I understand how my interaction with the HHMT impacts HH performance	243	2.9	16.9	56.4	23.9
I find it easy to get information from the HHMT	236	8.9	38.6	44.9	7.6
I sometimes find it difficult to use the HHMT	237	16.9	39.7	40.5	2.9
I sometimes find my interaction with the HHMT to be unclear	238	11.8	39.1	44.5	4.6
I sometimes find the HHMT hard to understand	238	9.7	59.2	28.2	2.9
Variable	n	Never	Occasionally	Sometimes	Always
I pay attention to the lights on activity counters	247	43.3	21.1	25.9	9.7
I look at HH performance on the monitor	247	24.7	24.3	30.4	20.7
I use the HHMT to track HH behavior	246	40.2	18.3	22.4	19.1
I discuss HH performance at staff huddles	245	32.7	14.3	22.5	30.6
I am reminded to perform HH by others	246	30.9	24.4	24.0	20.7
I remind others to perform HH	246	11.0	21.1	43.5	24.4

TABLE XIV: CORRELATION MATRIX FOR SURVEY QUESTIONS

	Nurse	Female	Smart phone	Apps	Clinical Always	Very Familiar HHMT	Contrib ute	Perceived Usefulnes s	Perceived Ease of Use	System use	Remind others
Nurse	1.0	0.42	-0.02	-0.07	0.24	0.31	0.09	0.27	0.20	0.41	0.32
Female	0.41	1.0	-0.02	-0.04	0.05	0.01	-0.02	0.05	-0.06	0.13	0.07
Smart phone	-0.02	-0.02	1.0	-	0.02	-0.05	-0.04	-0.001	0.08	-0.04	0.10
Apps	-0.07	-0.04	-	1.0	0.17	0.04	0.14	0.02	0.05	0.04	00.01
Clinical Always	0.24	0.05	0.02	0.17	1.0	0.	0.08	-0.18	-0.09	0.05	--0.06
Very Familiar HHMT	0.31	0.01	-0.05	0.04	0	1.0	0.09	0.15	0.36	0.49	0.25
Contribute	0.09	-0.02	-0.04	0.14	0.08	0.09	1.0	0.27	0.12	0.21	0.17
Perceived Usefulness	0.27	0.05	-0.01	0.02	-0.18	0.15	0.27	1.0	0.46	0.30	0.33
Perceived Ease of Use	0.20	-0.06	0.08	0.05	-0.09	0.36	0.12	0.46	1.0	0.42	0.22
System use	0.41	0.13	-0.04	0.04	0.05	0.49	0.21	0.32	0.30	1.0	0.49
Remind others	0.32	0.07	0.10	0.01	-0.06	0.25	0.17	0.33	0.22	0.49	1.0

ii. Assessment of conceptual constructs

Each composite variable was assessed for strength of interrelatedness among questions combined to represent the constructs perceived usefulness, perceived ease of use, and self-reported system use using Chronbach's alpha. As shown in Table XV, perceived usefulness was a particularly strong construct (alpha: 0.91) and self-reported system use displayed strong interrelatedness (alpha: 0.80). However, perceived ease of use (alpha: 0.60) displayed weak interrelatedness.

Responses to each of the questions comprising 'perceived ease of use' were heavily weighted towards neutral responses. This minimized variation in individual item responses may partially explain the weak interrelatedness seen for the construct perceived ease of use. Additionally, the passive nature of the HHMT, which does not require conscious interaction of the user, may have complicated the ability to conceptualize how an individual uses this system. For example, while an individual's movement throughout a unit triggers 'count' data within the hand hygiene monitoring technology, reported hand hygiene performance rates are at the unit-level. Furthermore, this HHMT does not utilize reminders such as audible sounds or the vibration of a wearable device when hand hygiene is not performed. Therefore, conceptualizing one's own interaction with the GOJO SMARTLINK™ system may be complicated for the end user. Despite the weakness of this construct, analysis was conducted for perceived ease of use given its role in the Technology Assessment Model although interpretations of predictor relationships with this construct should be approached with caution.

TABLE XV. ASSESSMENT OF INTERRELATEDNESS AMONG CONCEPTUAL CONSTRUCTS

	Sign	item-test corr	item-rest corr	alpha
Perceived usefulness **n: 215** mean: 8.4 (min: 0, max: 15)				**0.91**
I find the HHMT useful in my job	+	0.81	0.72	0.89
The HHMT is useful for understanding HH performance	+	0.87	0.80	0.88
I believe the HHMT is a good approach to measuring HH	+	0.87	0.81	0.88
I believe the HHMT is a good approach to improving HH	+	0.82	0.74	0.89
The HHMT promotes hand hygiene as a priority	+	0.76	0.66	0.90
I believe the HHMT is accurate at measuring HH behavior	+	0.83	0.74	0.89
Perceived ease of use **n:215** mean: 10. 9 (min: 4, max: 15)				**0.60**
I understand how my interaction with the HHMT impacts HH performance	+	0.52	0.23	0.61
I find it easy to get information from the HHMT	+	0.52	0.21	0.63
I sometimes find it difficult to use the HHMT[1]	+	0.61	0.33	0.57
I sometimes find my interaction with the HHMT to be unclear[1]	+	0.81	0.63	0.38
I sometimes find the HHMT hard to understand[1]	+	0.65	0.44	0.51
Self-reported system use **n: 215** mean: 4.3 (min: 0, max: 10)				**0.80**
I pay attention to the lights on activity counters	+	0.75	0.49	0.87
I look at HH performance on the monitor	+	0.89	0.73	0.63
I use the HHMT to track HH behavior	+	0.89	0.72	0.64

[1]Order of variable responses were reversed from negative to positive constructs prior to creating composite variable

Among the 259 participants, 17% had at least 1 missing value to a question contributing to the outcomes perceived usefulness or perceived ease of use. These respondents were removed, leaving 215 participants in the final analysis. Distribution of respondent job roles, belief in the ability to contribute to HH performance, and reminding others to perform hand hygiene were similar between respondents with missing data and those providing complete information for the outcomes of interest.

iii. Perceived usefulness

Linear regression was used to assess crude associations between predictor variables and the outcome perceived usefulness (Table XVI). Compared to men, women reported 0.13 points greater perceived usefulness of the technology, although this difference was non-statistically significant ($p = 0.843$). Nursing staff were likely to report values of perceived usefulness 1 point less than other respondents, although job role was non-significant ($p = 0.069$). Compared to others, respondents whose duties are always clinical reported 1.49 points less perceived usefulness of the HHMT ($p = 0.020$).

Neither ownership of a smart phone ($p = 0.854$) nor frequent use of mobile apps ($p = 0.715$) were significantly predictive of perceived usefulness. Respondents very familiar with the technology reported 1.20 greater points perceived usefulness than did healthcare personnel less familiar with the technology ($p = 0.034$). For each point increase in one's belief that they can contribute to improving HH performance, perceived usefulness increased by 1.76 points ($p < 0.001$). Increased frequency of reminding others to perform HH and being reminded to perform HH by others were associated with a 1.44 and 1.04-point increase in perceived usefulness, respectively.

TABLE XVI. CRUDE ASSOCIATIONS BETWEEN PERCEIVED USEFULNESS AND PREDICTOR VARIABLES

Perceived usefulness	**n**	**Crude Beta**	**p-value**	**R-squared**
Gender				
Female vs. Male	215	0.13	0.843	0.0002
Job Role				
Nurse vs. Other	203	-1.00	0.069	0.0686
Frequency of Clinical Responsibilities				
Always Clinical vs. Sometimes/Occasionally/Never	214	-1.49	0.020	0.0253
Own a smartphone				
Yes vs. No	213	-0.33	0.854	0.002
Frequency of using phone apps				
Always vs. Sometimes/Occasionally/Never	208	-0.13	0.715	0.0007
Familiarity with HHMT				
Very Familiar vs. Somewhat/Not Very	212	1.20	0.034	0.0212
I can contribute to improving HH performance	214	1.76	<0.001	0.0676
I remind others to perform HH	214	1.44	<0.001	0.1136
I am reminded by others to perform HH	214	1.04	<0.001	0.0867

Stepwise backward-selection estimation using a conservative 0.10 p-value threshold was used to identify independent, statistically significant predictors for each outcome. Using this approach, the following variables were associated with perceived usefulness: belief in the ability to contribute to collective HH (p= 0.001), reminding others to perform HH (p <0.001) and job role of nurse (p= 0.005). These variables explained 20% of variation in perceived usefulness (R-squared 0.20) and had a significant F-test (p <0.0001).

Using unadjusted results from bivariate regression and correlation, frequency of clinical duties and an interaction term (frequency of clinical duties * nurse or physician job role) were added into the linear regression model. These variables were non-significant and reduced variance explained by the model; thus, they were removed. The final linear regression model chosen based on goodness of fit using variance explained and overall model significance was simply:

Perceived Usefulness = Belief in ability to contribute to HH + Reminds others + Job Role

Each point increase in one's belief in their ability to contribute to HH was associated with a 1.4-point increase in perceived usefulness ($p= 0.001$). Similarly, for each increase in reported frequency of reminding others to perform hand hygiene, a 1.35- point increase in perceived usefulness occurred ($p <0.001$). Finally, nurses were likely to report perceived usefulness scores 1.42 points less than their colleagues ($p= 0.005$).

During model selection, effect modification between job role and familiarity with the technology was identified. To control for this phenomenon, the model was stratified by familiarity with the technology (Very familiar vs. Somewhat/Not Very familiar). The majority of respondents reported being Very Familiar with the HHMT (n: 131). Among respondents who were Very Familiar with the HHMT, belief in the contribution that one can contribute to HH was the single most predictive factor for perceived usefulness of the system, with each point increase in belief associated with 1.84 points increased perceived usefulness ($p= 0.002$) when controlling for frequency of reminding others to perform HH and job role (Table XVI). Given the aggregate nature of the GOJO SMARTLINK™ system, this finding is quite plausible. Those very familiar with the technology reported a 0.97 point increase in perceived usefulness with each point increase in frequency of reminding others to perform hand hygiene ($p= 0.015$) while controlling for system familiarity and job role. Interestingly, among those Very Familiar with the technology, nurses were almost twice as likely to report negative perceptions of the usefulness of

HHMT compared to others, displayed by 2.12 decreased points in this construct ($p= 0.002$) while controlling for system familiarity and frequency of reminding others.

Among persons who were Somewhat or Not Very Familiar with the HHMT (n: 68), the single statistically significant predictor of perceived usefulness was reported participation in reminding others to perform hand hygiene. For each point increase in reported frequency of reminding others, a 1.75 point increase in perceived usefulness was observed ($p <0.001$) while controlling for belief in one's ability to contribute to HH ($p= 0.532$) and job role ($p= 0.795$).

The role of system familiarity plays an important role in perceived usefulness. Those who report being very familiar with the HHMT were more likely to find the technology useful as the belief in their own ability to contribute to hand hygiene performance increases. However, among those less familiar with the technology, those who actively engage in reminding others to perform hand hygiene reported strongest perceived usefulness of the HHMT. These results support greater perceptions of "it's not me, it's you" contributing to poor HH, seen to be prevalent during preliminary Voice of the Customer exercises, among those less familiar with the technology.

TABLE XVII: MULTIVARIATE LINEAR REGRESSION FOR PERCEIVED USEFULNESS

Perceived usefulness n: 201, R^2: 0.20	**Adjusted Coef.**	**Std. Err**	**95% CI**	**p-value**
Contribute	1.45	0.44	0.59, 2.31	0.001
Remind Others	1.35	0.27	0.82, 1.89	<0.001
Nurse vs. Other	-1.42	0.50	-2.40, -0.43	0.005

Perceived usefulness	**Very Familiar** n:131, R^2: 0.18				**Somewhat/Not Very Familiar** n:68, R^2: 0.32			
	Adjusted Coef.	**Std. Err**	**95% CI**	**p-value**	**Adjusted Coef.**	**Std. Err**	**95% CI**	**p-value**
Contribute	1.84	0.59	0.68, 3.01	0.002	0.37	0.59	-0.81, 1.54	0532
Remind Others	0.97	0.39	0.19, 1.75	0.015	1.75	0.32	1.11, 2.39	<0.001
Nurse vs. Other	-2.12	0.68	-3.47, -0.77	0.002	-0.16	0.62	-1.41, 1.08	0.795

iv. <u>Perceived ease of use</u>

Linear regression was used to assess crude associations between predictor variables and perceived ease of use (Table XVIII). Non-significant associations with perceived ease of use were seen for gender (p= 0.354), job role (p= 0.867), frequency of clinical responsibilities (p= 0.120), ownership of a smart phone (p= 0.074), and frequency of mobile app use (p= 0.336) (Table XVIII). Compared to those less familiar with the technology, respondents who were Very Familiar with the HHMT reported 1.62 points greater perceived ease of use (p <0.001). For each increase in frequency of reminding others to perform hand hygiene, a 0.72-point increase in perceived ease of use was observed (p <0.001). Unlike the crude associations seen with perceived usefulness, neither belief in one's own ability to contribute to HH (p= 0.099) nor increased frequency in being reminded to perform HH by others (p= 0.104) were significantly predictive of perceived ease of using the technology.

TABLE XVIII. CRUDE ASSOCIATIONS BETWEEN PERCEIVED EASE OF USE AND PREDICTOR VARIABLES

Perceived ease of use	N	Coeff.	P-value	R-squared
Gender Female vs. Male	215	-0.01	0.354	0.0040
Job Role Nurse vs. Other	203	0.05	0.867	0.0001
Frequency of Clinical Responsibilities Always Clinical vs. Occasionally/Never	214	-0.58	0.120	0.0114
Own a smartphone Yes vs. No	213	1.83	0.074	0.0744
Frequency of using phone apps	208	0.19	0.336	0.0045
Familiarity with HHMT Very Familiar vs. Somewhat/Not Very/Not at all	212	1.62	<0.001	0.1174
I can contribute to improving collective HH performance	214	0.44	0.099	0.0989
I remind others to perform HH	214	0.72	<0.001	0.0874
I am reminded by others to perform HH	214	0.23	0.104	0.0124

Stepwise backward-selection estimation using a conservative 0.10 p-value threshold was again used to identify statistically significant predictors for perceived ease of use. Using this approach, the following variables were associated with this outcome: familiarity with HHMT (p <0.001) and reminding others to perform hand hygiene (p= 0.001). These variables explained 16% of variation in perceived usefulness (R-squared 0.16) and had a significant F-test (p <0.0001). This low proportion of explained variation in the model may partially be explained by the poor interrelatedness of the outcome construct perceived ease of use. Further iterative modeling of potential confounding effects and effect modification did not result in a model more appropriate for the data. Specifically, job role was not predictive of this outcome. Thus, the final model remained:

Perceived Ease of Use = Reminds others + Familiarity with the HHMT

Compared to those less familiar with the technology, participants very familiar with the HHMT reported 1.39 greater points perceived ease of use ($p < 0.001$) while controlling for frequency of reminding others to perform hand hygiene. Additionally, for each point increase in frequency of reminding others to perform HH, a 0.55-point increase in perceived ease of use was observed ($p = 0.001$) while controlling for familiarity with the system.

TABLE XIX. MULTIVARIATE LINEAR REGRESSION FOR PERCEIVED EASE OF USE

Perceived Ease of Use n: 211, R^2: 0.16	**Adjusted Coef.**	**Std. Err**	**95% CI**	**p-value**
Familiarity with HHMT Very Familiar vs. Somewhat/Not Very/Not at all	1.39	0.31	0.79, 2.00	<0.001
I remind others to perform HH	0.55	0.15	0.23, 0.86	0.001

v. Self-reported HHMT utilization

Linear regression was used to assess crude associations between predictor variables and system use (Table XX). Non-significant associations with perceived ease of use were seen for frequency of clinical responsibilities ($p= 0.842$), ownership of a smartphone ($p= 0.338$), and frequency of mobile app use ($p= 0.822$). Compared to males, females reported 1.15 greater points on the scale of system use ($p= 0.014$), an association likely explained by the higher frequency of female respondents working as nurses, which was also significantly associated with reported system use ($p <0.001$). Those very familiar with the HHMT reported 1.74 points greater frequency of system use compared to those less familiar ($p <0.001$). For each point increase in belief in one's ability to contribute to hand hygiene performance, a 1-point increase in reported system use was observed ($p= 0.002$). Both increased frequency of reminding others to perform HH ($p <0.001$) and being reminded ($p <0.001$) were associated with increased system utilization (Table XX). Finally, for each 1-point increase in perceived ease of use and perceived usefulness a 0.48 ($p <0.001$) and 0.20 ($p <0.001$) point increase in reported system use was observed, respectively.

TABLE XX. CRUDE ASSOCIATIONS BETWEEN SYSTEM USE AND PREDICTOR VARIABLES

System use of use crude associations	N	Crude Beta	P-value	R-squared
Gender Female vs. Male	215	1.15	0.014	0.0282
Job Role Nurse vs. Other	203	1.49	<0.001	0.0730
Frequency of Clinical Responsibilities Always Clinical vs. Occasionally/Never	214	0.09	0.842	0.0002
Own a smartphone Yes vs. No	213	-1.21	0.338	0.0043
Frequency of using phone apps	208	-0.06	0.822	0.0002
Familiarity with HHMT Very Familiar vs. Somewhat/Not Very/Not at all	212	1.74	<0.001	0.0907
I can contribute to improving collective HH performance	214	1.00	0.002	0.0441
I remind others to perform HH	214	1.54	<0.001	0.2651
I am reminded by others to perform HH	214	0.80	<0.001	0.1048
Perceived Ease of Use	215	0.48	<0.001	0.1528
Perceived Usefulness	215	0.20	<0.001	0.0810

Stepwise backward-selection estimation using a conservative 0.10 p-value threshold was again used to identify statistically significant predictors for self-reported system use. Using this approach, the following variables were associated with this outcome: reminding others to perform HH (p <0.001), perceived ease of use (p <0.001), job role nurse vs. other (p <0.001), being reminded to perform HH by others (p= 0.060), and ownership of a smartphone (p= 0.006). These variables explained 41% of variation in perceived usefulness (R-squared 0.41) and had a significant F-test (p <0.0001). Iterative modeling of potential confounding effects and effect modification found the removal of being reminded by others to minimally affect the fit of this model. Ownership of a smartphone was removed as 98% of respondents reported smart phone ownership. Additionally, following the TAM, perceived usefulness was forced into the model. This addition led to the following model:

System Use = Perceived Usefulness + Perceived Ease of Use + Reminds Others + Nurse

These variables explained 40% of variation in perceived usefulness (R-squared 0.40) and had a significant F-test ($p < 0.0001$). When controlling for other variables, perceived usefulness was non-significantly predictive of system utilization ($p = 0.370$) (Table XXI). For each point increase in perceived ease of use, a 0.31 increase in system use was observed ($p < 0.001$). Nurses reported 1.32 points higher on the system utilization scale compared to others ($p < 0.001$) while each point increase in frequency of reminding others to perform HH was associated with a 1.15 point increase in system use ($p < 0.001$).

In order to control for effect modification existing between job role and familiarity with the technology, identified previously, this model was stratified by familiarity with the HHMT (Very familiar vs. Somewhat/Not Very familiar) (Table XXI). This stratification indicated that increased frequency of reminding others to perform hand hygiene was associated with increased frequency of system use in both those very familiar and less familiar with the HHMT. While being familiar with the system is intuitively predictive of system use and perceived usefulness of any technology, the association between reminding others to perform HH and system use supports efforts to increase participation in promotion of collective hand hygiene performance in order to increase system use and perceived usefulness.

TABLE XXI. MULTIVARIATE LINEAR REGRESSION FOR SYSTEM USE

System Use n: 202, R^2: 0.38	**Adjusted Coef.**	**Std. Err**	**95% CI**	**p-value**
Perceived Usefulness	0.04	0.05	-0.05, 0.13	0.370
Perceived Ease of Use	0.31	0.08	0.16, 0.47	<0.001
Remind Others	1.15	0.18	0.79, 1.51	<0.001
Nurse vs. Other	1.32	0.32	0.69, 1.94	<0.001

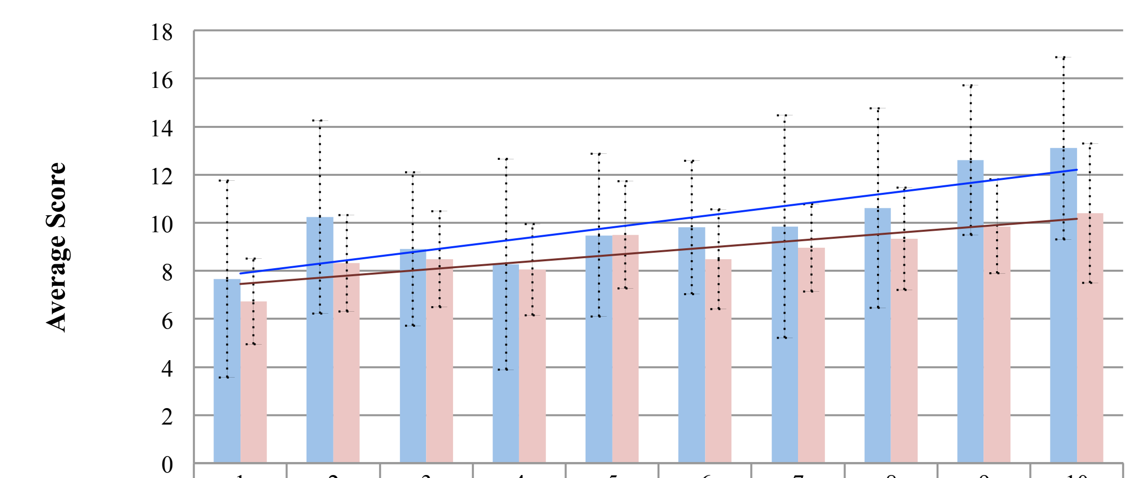
System Use	**Very Familiar** n:131, R^2: 0.33				**Somewhat/Not Very Familiar** n:69, R^2: 0.32			
	Adjusted Coef.	**Std. Err**	**95% CI**	**p-value**	**Adjusted Coef.**	**Std. Err**	**95% CI**	**p-value**
Perceived Usefulness	0.05	0.06	-0.06, 0.16	0.349	0.09	0.10	-0.11, 0.30	0.373
Perceived Ease of Use	0.22	0.10	0.02, 0.42	0.034	0.30	0.15	0.01, 0.60	0.047
Remind Others	1.30	0.24	0.82, 1.78	<0.001	0.75	0.31	0.12, 1.37	0.020
Nurse vs. Other	1.30	0.42	0.46, 2.12	0.002	1.07	0.50	0.06, 2.07	0.038

In addition to this model, the predictive power of just perceived ease of use and perceived usefulness on system utilization was explored, aligning with the framework in Technology Assessment Model (Table XXII). Combined, perceived ease of use and perceived usefulness explained 17% of the variance in self-reported system use. Perceived ease of use was statistically significantly predictive of reported interaction with the technology ($p < 0.001$) while perceived usefulness was non-statistically significant ($p = 0.066$).

TABLE XXII: PREDICTIVE POWER OF PERCEIVED USEFULNESS AND PERCEIVED EASE OF USE ON SYSTEM USE

System Use n: 215, R^2: 0.17	**Adjusted Coef.**	**Std. Err**	**95% CI**	**p-value**
Perceived Usefulness	0.09	0.05	-0.01, 0.19	0.066
Perceived Ease of Use	0.40	0.09	0.23, 0.57	<0.001

The linear relationship between both perceived usefulness and perceived ease of use with system use is visualized in Figure 5. While the slope of the linear relationship between perceived usefulness and system use is more inclined, the large amount of variability in this variable is noteworthy (Figure 5). Conversely, the impact of perceived ease of use was seen to have comparatively small standard deviations in mean responses across levels of reported system use (Figure 5). Again, the impact of perceived ease of use should be interpreted with caution given the poor interrelatedness of this construct.



	1	2	3	4	5	6	7	8	9	10
Usefulness	7.65	10.24	8.9	8.27	9.48	9.8	9.84	10.6	12.6	13.1
Ease	6.73	8.32	8.48	8.05	9.5	8.48	8.95	9.33	9.85	10.4

Figure 5. Mean perceived usefulness (PU) and perceived ease of use (PE) across system use

vi. <u>Discussion</u>

While this study was exploratory in nature, it was hypothesized that a strong belief in the benefits of collective HH behaviors would predict stronger perceptions around ease of use and usefulness of an aggregate-level HHMT. This association held with belief in one's ability to contribute to hand hygiene significantly predicting perceived usefulness (Table XVII). However, this relationship was stronger among persons very familiar with the HHMT compared to those somewhat or not very familiar with the technology. The variable "I remind others to perform hand hygiene" may best represent the association between belief in the benefits of group hand hygiene and use of HHMT as it was significantly predictive of perceived usefulness ($p < 0.001$), perceived ease of use ($p < 0.001$), and self-reported use of the hand hygiene monitoring technology ($p < 0.001$).

There were a number of limitations to this study. First, 17% of responses were identified to have missing data associated with the outcomes in question, resulting in exclusion from this analysis. Alternative approaches to handling missing data may have proved useful if previously reported data on this topic were available. However, the novelty of this study prohibited imputation using data from the literature. Second, the construct perceived ease of use was seen to have poor interrelatedness. While investigators hypothesize the aggregate nature of this HHMT is likely to complicate the end user's perception of individual 'use' of this technology, this construct cannot reliably be interpreted from this analysis.

vii. Conclusions

The results of this survey study showcase the first known attempt to conceptualize healthcare personnel acceptance of hand hygiene monitoring technology using established social cognition theories as the underlying framework. In general, perceptions of the ease of using and the usefulness of the GOJO SMARTLINK™ system were moderately strong. Average perceived ease in using the technology was 8.6 (standard deviation: 2.3) on a 15-point scale; however, this composite variable was weakly interrelated. Average usefulness of the HHMT, which was a strongly interrelated construct, was 9.7 (standard deviation: 4.0) on an 18-point scale. In general, belief in the ability of oneself to contribute to hand hygiene performance as well as participation in collective hand hygiene performance by reminding others to perform HH were the most highly predictive characteristics of reported system usefulness and system use. These results support the existence of a relationship between perceived benefits of group hand hygiene performance and the perceived usefulness and reported use of a hand hygiene monitoring technology that measures hand hygiene at the unit level.

Further research is needed to assess the strength of this relationship when applied to perceived benefits of individual hand hygiene and intention to use technologies to measure HH behaviors at the individual level. Additionally, efforts to increase responses among physicians and ancillary staff will improve the ability to generalize findings among healthcare providers. In order to improve perceived usefulness of the aggregate-level hand hygiene monitoring technology, efforts dedicated towards creating a culture that values hand hygiene not only at an individual level but also as a collective goal may prove beneficial. Finally, the ability to link intentions to use hand hygiene monitoring technology with hand hygiene performance is a recommended future step towards understanding user acceptance and usefulness of these technologies.

C. Aim 3 Results

Between January 1, 2014 and February 29, 2016, patients throughout the hospital were an average 55 years of age (range: 0-84) with an average Charlson Comorbidity Index of 4.22 (range: 0.19 – 6.84). Average length of stay was 12.1 days (range: 1-73) among those infected with any HAI and 6.18 days across the entire population. Among the 28 hospital units, 9 were intensive care units, 19 were inpatient floors, 4 units cared for pediatric patients, and 24 units cared for adult patients (Table XXIII).

TABLE XXIII. HOSPITAL UNIT CHARACTERISTICS

Characteristic	Number	Percent
Patient Population Cared For		
Adult patients	24	85.7
Pediatric Patients	4	14.3
Intensive care setting		
ICU	9	33.1
Floor	19	67.9
Proportion of visitors		
0 – 13.2%	8	28.6
13.3% - 17.6%	5	17.9
17.7% - 20.5%	5	17.9
20.6% - 41.7%	5	17.9
Missing	5	17.9

To investigate relationships among the metrics under analysis, correlations were explored among all pairs of variables (Table XXIV). As anticipated, older age was associated with higher Charlson Comorbidity Index (r: 0.06), risk of MRSA colonization (r: 0.08) and infection (r: 0.04), as well as decreased length of stay (r: -0.14). This was anticipated due to increased mortality among older patients with higher clinical acuity. Of interest, hand hygiene performance rates were strongly correlated across date of admission, date of culture swab, and date of infection sample collection. This finding was anticipated based on quality improvement and change theory supporting common behaviors in micro-cultures. In other words, hand hygiene remains correlated on a single hospital unit.

TABLE XXIV. CORRELATION MATRIX AMONG HAND HYGIENE AND HAI VARIABLES AT THE UNIT LEVEL

	Age	Colonized	Charlson index	HH Rate	LOS	Visitors	MRSA acquisition	*C. difficile* acquisition	VRE acquisition
Age	1.0	**0.03**	**0.62**	-0.05	-0.11	0.07	-0.08	-0.07	-0.51
Colonized	0.03	1.0	**-0.28**	**0.56**	-0.06	**-0.54**	0.13	-0.13	-0.37
Charlson index	**0.62**	**-0.28**	1.0	**-0.23**	0.02	**0.13**	-0.13	0.09	-0.28
HH Rate	-0.05	**0.56**	**-0.23**	1.0	-0.02	**-0.59**	0.10	0.12	-0.23
LOS	-0.11	-0.06	0.02	-0.02	1.0	-0.07	0.03	0.14	0.06
Visitors	0.07	**-0.54**	**0.13**	**-0.59**	-0.07	1.0	-0.09	-0.17	0.22
MRSA acquisition	-0.08	0.13	-0.13	0.10	0.03	-0.09	1.0	-0.17	-0.16
C. difficile acquisition	-0.07	-0.13	0.09	0.12	0.14	-0.17	-0.17	1.0	0.36
VRE acquisition	-0.51	-0.37	0.28	-0.23	0.06	0.22	-0.16	0.36	1.0

i. <u>MRSA diagnosed greater than 48hrs from admit in non-colonized patients</u>

A total of 290 positive cultures were identified among inpatients during the period of analysis. Of these, 121 cultures were ordered after 48 hours from patient admission, 45 positive cultures were attributed to patients who screened negative for colonization upon admission, and 30 cultures were ordered after 48 hours from patient admission in non-colonized patients. Incidence of MRSA acquisition among non-colonized patients, identified >48 hours after admission, was 2.7 per 10,000 patient days. Using an average length of stay of 6.18 days, this equates to 0.17% incidence within the patient population (Table XXV).

TABLE XXV. INCIDENCE OF ACQUISITION OF MRSA, *C.DIFFICILE*, AND VRE

Organism	Average Incidence per 10,000 pt-days	Average Incidence per patient x 100
MRSA acquisition		
In non-colonized patients	2.7	0.17%
Standard def: >48hrs after admission	8.2	0.51%
***C. difficile* acquisition**	7.7	0.48%
VRE acquisition	3.9	0.24%
Acquisition of MRSA, Cdiff or VRE All defined as >48hrs	17.4	1.08%

Hand hygiene was significantly correlated with colonization pressure. With an Incident Rate Ratio of 1.06 ($p < 0.001$), for every 1% increase in colonization pressure, HH was seen to increase by 5.97%. This intuitively makes sense given the likelihood of increasing compliance with hand hygiene upon knowledge that a patient is colonized with MRSA. Similarly, colonization pressure was significantly predictive of acquisition of MRSA among non-colonized patients >48 hours after admission with an IRR of 1.25 ($p < 0.001$), equating to a 25% increase in average risk of MRSA acquisition for every 1% increase in colonization pressure. Colonization pressure was verified as a confounding factor in the relationship between hand hygiene and acquisition of MRSA.

After establishment of a significant effect of colonization pressure on HH performance, exploration of a potential bidirectional relationship between HH performance and acquisition of MRSA was explored. The hypothesis was that as incidence of MRSA increases throughout a hospital environment, healthcare providers are more likely to perform hand hygiene. This effect was validated with an IRR of 1.003 ($p= 0.001$), for every 1% increase in acquisition of MRSA >48 hours after admission in non-colonized patients, average hand hygiene performance increased by 0.33%. In order to account for this effect of MRSA incidence on hand hygiene, predictions of expected log(means of HH performance) were calculated using post-estimation commands following Poisson regression of hand hygiene by incidence of acquisition. These predicted log(means of HH performance) were subtracted from overall HH performance in order quantify the exposure of interest, HH, which was not affected by the incidence of MRSA acquisition. This remaining incidence was then modeled as the exposure of interest to predict acquisition of MRSA, while controlling for the confounding variable colonization pressure:

Expected log (mean of incidence) = 0.2237 – 0.0454 (HH performance not influenced by incidence) + 0.2944 (colonization pressure)

Next, the effect of HH performance and colonization pressure were quantified using predictions of expected log(means of incidence) calculated using post-estimation commands.

These predicted log(means of incidence) were subtracted from overall MRSA incidence in order to quantify incidence of MRSA acquisition that was not affected by HH and colonization pressure. This remaining incidence was then modeled against the potential confounding variables: average age of patients cared for, average Charlson Comorbidity Index, month, status of the unit as an ICU or floor setting, and proportion of visitors contributing to hand hygiene opportunities (room entries and exits). Again using Poisson regression, the effect of potential confounding variables on incidence of hospital-acquired acquisition of MRSA that was not explained by HH performance or colonization pressure was:

Expected log (mean of incidence not effected by HH or colonization pressure) = -0.4515 + 0.0539(age) - 0.8659(Charlson index) + 1.4952(ICU) + 0.1586(month) – 0.5073(visitors)

The intention of this analysis was to quantify the relationship between HH performance and incidence of hospital-acquired acquisition of organisms rather than to predict true incidence of acquisition. Therefore, since the intercepts were not important for interpretation, these equations were merged to the following:

Expected log (mean of incidence) = -0.2278 – 0.0454 (HH performance not influenced by incidence) + 0.2944 (colonization pressure) + 0.0539(age) - 0.8659(Charlson index) + 1.4952(ICU) + 0.1586(month) – 0.5073(visitors)

The impact of hand hygiene on acquisition of MRSA >48 hours after admission among patients with documented status of non-colonization upon admission was statistically significant with an IRR of 0.96 (p <0.001) which equates to a 4.4% decrease in incidence for every 1% increase in hand hygiene performance while controlling for colonization pressure (Table XXVI). This accounts for the impact of potential confounding factors including average age and underlying comorbidities of patients, proportion of visitors contributing to HH opportunities, and ICU or inpatient floor setting.

ii. <u>MRSA diagnosed greater than 48 hours after admission</u>

Incidence of MRSA acquisition using the standard definition of diagnosis >48 hours after admission, was 8.2 per 10,000 patient days. Using an average length of stay of 6.18 days, this equates to 0.51% incidence within the patient population (Table XXV).

Hand hygiene was significantly correlated with colonization pressure. With an Incident Rate Ratio of 1.06 ($p < 0.001$), for every 1% increase in colonization pressure, HH was seen to increase by 5.97%. This intuitively makes sense given the likelihood of increasing compliance with hand hygiene upon knowledge that a patient is colonized with MRSA. Similarly, colonization pressure was significantly predictive of acquisition of MRSA >48 hours after admission with an IRR of 1.11 ($p < 0.001$), equating to an 11% increase in average risk of MRSA acquisition for every 1% increase in colonization pressure. Colonization pressure was verified as a confounding factor in the relationship between hand hygiene and acquisition of MRSA.

After establishment of a significant effect of colonization pressure on HH performance, exploration of a potential bidirectional relationship between HH performance and acquisition of MRSA was explored. The hypothesis was that as incidence of MRSA increases throughout a hospital environment, healthcare providers are more likely to perform hand hygiene. This effect was validated with an IRR of 1.002 ($p = 0.011$), for every 1% increase in acquisition of MRSA >48 hours after admission, average hand hygiene performance increased by 0.22%. In order to account for this effect of MRSA incidence on hand hygiene, predictions of expected log(means of HH performance) were calculated using post-estimation commands following Poisson regression of hand hygiene by incidence of acquisition. These predicted log(means of HH performance) were subtracted from overall HH performance in order quantify the exposure of interest, HH, that was not affected by the incidence of MRSA acquisition. This remaining incidence was then modeled as the exposure of interest to predict acquisition of MRSA, while controlling for the confounding variable colonization pressure:

Expected log (mean of incidence) = 1.8293 – 0.0193 (HH performance not influenced by incidence) + 0.1407 (colonization pressure)

Next, the effect of HH performance and colonization pressure were quantified using predictions of expected log(means of incidence) calculated using post-estimation commands. These predicted log(means of incidence) were subtracted from overall MRSA incidence in order to quantify incidence of MRSA acquisition that was not affected by HH and colonization pressure. This remaining incidence was then modeled against the potential confounding variables: average age of patients cared for, average Charlson Comorbidity Index, month, status of the unit as an ICU or floor setting, and proportion of visitors contributing to hand hygiene opportunities (room entries and exits). Again using Poisson regression, the effect of potential confounding variables on incidence of hospital-acquired acquisition of MRSA that was not explained by HH performance or colonization pressure was:

Expected log (mean of incidence not effected by HH or colonization pressure) = 1.5000 + 0.3005(age) - 0.5616(Charlson index) + 0.2667(ICU) + 0.1393(month) – 0.3037(visitors)

The intention of this analysis was to quantify the relationship between HH performance and incidence of hospital-acquired acquisition of organisms rather than to predict true incidence of

acquisition. Therefore, since the intercepts were not important for interpretation, these equations were merged to the following:

Expected log (mean of incidence) = 3.3293 – 0.0193 (HH performance not influenced by incidence) + 0.1407 (colonization pressure) + 0.3005(age) - 0.5616(Charlson index) + 0.2667(ICU) + 0.1393(month) – 0.3037(visitors)

The impact of hand hygiene on acquisition of MRSA >48 hours after admission was statistically significant with an IRR of 0.98 (p= 0.031) which equates to a 1.9% decrease in incidence for every 1% increase in hand hygiene performance while controlling for colonization pressure (Table XXVI). This accounts for the impact of potential confounding factors including average age and underlying comorbidities of patients, proportion of visitors contributing to HH opportunities, and ICU or inpatient floor setting.

iii. *Clostridium difficile*

Across the period of analysis, among units with the HHMT, incidence of *C. difficile* acquisition greater than 48 hours after admission was 7.74 per 10,000 patient days. Using an average length of stay of 6.18 days, this equates to 0.48% incidence within the patient population (Table XXIV). Using Poisson regression, the effect of hand hygiene performance on hospital-acquired acquisition of *C. difficile* was found to be:

Expected log (mean of incidence) = 0.3734 – 0.0165 (HH Rate)

The effect of hand hygiene was statistically significant (p= 0.042). Predictions of expected log(means of incidence) were calculated using post-estimation commands. These predicted log(means of incidence) were subtracted from overall incidence of *C. difficile* to quantify the incidence that was not effected by hand hygiene performance. This remaining incidence was then modeled against the potential confounding variables: average age of patients cared for, average Charlson Comorbidity Index, month, status of the unit as an ICU or floor setting, and proportion of visitors contributing to hand hygiene opportunities (room entries and exits). Again using Poisson regression, the effect of potential confounding variables on incidence of hospital-acquired acquisition of *C. difficile* that was not explained by HH performance was:

Expected log (mean of incidence not effected by HH) = -0.2785 + 0.0051(age) + 0.1303(Charlson index) + 0.3149(ICU) – 0.0590(month) - 0.1.008(visitors)

The intention of this analysis was to quantify the relationship between HH performance and incidence of hospital-acquired acquisition of organisms rather than to predict true incidence of acquisition. Therefore, since the intercepts were not important for interpretation, these equations were merged to the following:

Expected log (mean of incidence) = 0.0949– 0.0165 (HH Rate) + 0.0051(age) + 0.1303(Charlson index) + 0.3149(ICU) – 0.0590(month) - 0.1.008(visitors)

The impact of hand hygiene on acquisition of *C. difficile* was statistically significant with an IRR of 0.98 (p= 0.042) which equates to a 1.64% decrease in incidence for every 1% increase in hand hygiene performance (Table XXIV). This accounts for the impact of potential confounding factors including average age and underlying comorbidities of patients, proportion of visitors contributing to HH opportunities, and ICU or inpatient floor setting.

iv. Vancomycin-resistant *Enterococci*

Across the period of analysis, among units with the HHMT, incidence of VRE acquisition greater than 48 hours after admission was 3.90 per 10,000 patient days. Using an average length of stay of 6.18 days, this equates to 0.24% incidence within the patient population (Table XXIV). Using Poisson regression, the effect of hand hygiene performance on hospital-acquired acquisition of *C. difficile* was:

Expected log (mean of incidence) = -1.6555 + 0.0177 (HH Rate)

The effect of hand hygiene was non-statistically significant (p= 0.069). Predictions of expected log(means of incidence) were calculated using post-estimation commands. These predicted log(means of incidence) were subtracted from overall incidence of VRE to quantify the incidence that was not effected by hand hygiene performance. This remaining incidence was then modeled against the potential confounding variables: average age of patients cared for, average Charlson Comorbidity Index, month, status of the unit as an ICU or floor setting, and proportion of visitors contributing to hand hygiene opportunities (room entries and exits). Again using Poisson regression, the effect of potential confounding variables on incidence of hospital-acquired acquisition of VRE that was not explained by HH performance was:

Expected log (mean of incidence not effected by HH) = 7.5171 - 0.0386(age) – 0.1651(Charlson index) – 3.5000(ICU) – 0.2336(month) – 1.2569(visitors)

The intention of this analysis was to quantify the relationship between HH performance and incidence of hospital-acquired acquisition of organisms rather than to predict true incidence of

acquisition. Therefore, since the intercepts were not important for interpretation, these equations were merged to the following:

Expected log (mean of incidence) = 5.8616+ 0.0177 (HH Rate) - 0.0386(age) – 0.1651(Charlson index) – 3.5000(ICU) – 0.2336(month) – 1.2569(visitors)

The impact of hand hygiene on acquisition of VRE was non-statistically significant with an IRR of 1.02 (p= 0.069) which equates to a 1.79% increase in incidence for every 1% increase in hand hygiene performance (Table XXVI). This accounts for the impact of potential confounding factors including average age and underlying comorbidities of patients, proportion of visitors contributing to HH opportunities, and ICU or inpatient floor setting. The unanticipated directionality of this relationship is hypothesized to be explained by the rarity of the event. During the 19-month period, only 39 acquisition events occurred using the standard surveillance definition of diagnosis >48 hours after admission. Therefore, this analysis was likely not powered to interpret these results with confidence.

v. <u>Any acquisition greater than 48 hours after admission</u>

Across the period of analysis, among units with the HHMT, incidence of MRSA, *C. difficile*, or VRE acquisition greater than 48 hours after admission was 17.4 per 10,000 patient days. Using an average length of stay of 6.18 days, this equates to 1.08% incidence within the patient population (Table XXIV). Hand hygiene was significantly correlated with colonization pressure. With an Incident Rate Ratio of 1.06 (p <0.001), for every 1% increase in colonization pressure, HH was seen to increase by 5.97%. This intuitively makes sense given the likelihood of increasing compliance with hand hygiene upon knowledge that a patient is colonized with MRSA. Similarly, colonization pressure was significantly predictive of acquisition of MRSA, *C.*

difficile, or VRE >48 hours after admission with an Incidence Rate Ratio (IRR) of 1.05 (p= 0.045), equating to a 5% increase in average risk of MRSA acquisition for every 1% increase in colonization pressure. Colonization pressure was verified as a confounding factor in the relationship between hand hygiene and acquisition of the 3 pathogens as a combined outcome. Using Poisson regression, the effect of hand hygiene performance on hospital-acquired acquisition of infection while controlling for colonization pressure was found to be:

Expected log (mean of incidence) = 2.8579 – 0.0024(HH Rate) + 0.0550 (colonization pressure)

Next, the effect of HH performance and colonization pressure were quantified using predictions of expected log(means of incidence) calculated using post-estimation commands. These predicted log(means of incidence) were subtracted from overall MRSA incidence in order to quantify incidence of MRSA acquisition that was not affected by HH and colonization pressure. This remaining incidence was then modeled against the potential confounding variables: average age of patients cared for, average Charlson Comorbidity Index, month, status of the unit as an ICU or floor setting, and proportion of visitors contributing to hand hygiene opportunities (room entries and exits). Again using Poisson regression, the effect of potential confounding variables on incidence of hospital-acquired acquisition of MRSA that was not explained by HH performance or colonization pressure was:

Expected log (mean of incidence not effected by HH or colonization pressure) = 3.6658 + 0.0036(age) - 0.1047(Charlson index) – 0.0775(ICU) - 0.0271(month) – 0.2402(visitors)

The intention of this analysis was to quantify the relationship between HH performance and incidence of hospital-acquired acquisition of organisms rather than to predict true incidence of

acquisition. Therefore, since the intercepts were not important for interpretation, these equations were merged to the following:

Expected log (mean of incidence) = 0.8079 – 0.0024(HH Rate) + 0.0550 (colonization pressure) + 0.0036(age) - 0.1047(Charlson index) – 0.0775(ICU) - 0.0271(month) – 0.2402(visitors)

The impact of hand hygiene on acquisition of MRSA, *C. difficile,* or VRE greater than 48 hours after admission was non-statistically significant with an IRR of 0.99 (p= 0.734). However, this equates to a 0.24% decrease in incidence for every 1% increase in hand hygiene performance while controlling for colonization pressure, which may be clinical and financially significant (Table XXVI).

TABLE XXIV. RELATIONSHIP BETWEEN INCIDENCE OF ACQUISITION AND HH RATE

Organism	# of infections	IRR	% Change	p-value
MRSA acquisition				
In non-colonized patients	30	0.96	-4.44%	<0.001
Standard def.: >48hrs after admission	121	0.98	-1.91%	0.031
***C. difficile* acquisition**	159	0.98	-1.64%	0.042
VRE acquisition	39	1.02	1.79%	0.681
Acquisition of MRSA, *C. difficile* or VRE All defined as >48hrs	319	0.99	-0.24%	0.734

This accounts for the impact of potential confounding factors including average age and underlying comorbidities of patients, proportion of visitors contributing to HH opportunities, and

ICU or inpatient floor setting. The relationship between incidence of acquisition of these pathogens and HH performance is displayed in Figure 6.

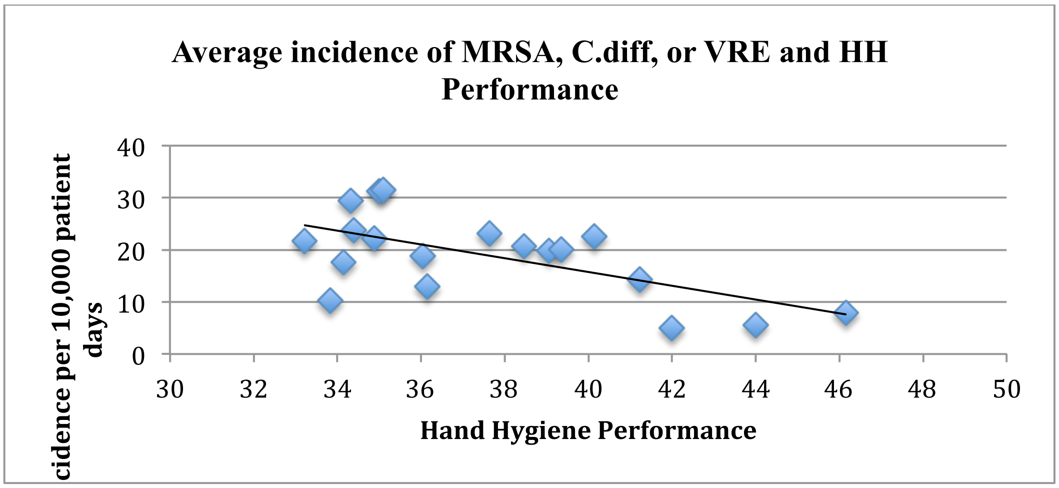


Figure 6. Scatter plot of relationship between HH and incidence of HAI

vi. Discussion

This analysis supports a clinically significant predictive relationship between hand hygiene performance and acquisition of pathogens in the healthcare setting using approximately 1.5 years of clinical data incorporating over 14 million hand hygiene events and over 40 million hand hygiene opportunities. Specifically, a 1% increase in hand hygiene was seen to decrease incidence of MRSA acquisition using standard surveillance definitions of hospital-acquired MRSA as diagnosed greater than 48 hours after admission, by 1.91% ($p = 0.031$). Using a more robust definition of hospital-acquired MRSA as diagnosed greater than 48 hours after admission in a patient screened negative for colonization upon admission, a 1% increase in hand hygiene was associated with a 4.44% ($p < 0.001$) decrease in incidence of MRSA acquisition.

Between August 1, 2014 and February 29, 2016, an estimated 45,483 patients were admitted to the medical center. Applying the average incidence of MRSA acquisition in non-colonized patients, 0.17%, 77 patients were expected to acquire MRSA during the 19-month period. While swabs to determine colonization status may be ordered across the medical center, active surveillance is limited to intensive care units. Thus, this outcome metric heavily represents patients cared for in the ICU setting rather than the broader inpatient population. An increase in 1% hand hygiene performance equates to 3.4 prevented acquisitions of MRSA in non-colonized patients. A single MRSA infection has been estimated to cost a hospital $50,000 (Cummings et al., 2010). Thus, for each 1% increase in HH performance, $170,934 was saved in prevention of hospital-acquired MRSA. In terms of yearly savings, a 1% increase in HH performance was estimated to prevent 2.1 MRSA infections annually, resulting in $106,408 savings each year using a strict definition of MRSA acquisition.

Similarly, a 1% increase in hand hygiene was associated with a 1.64% (p= 0.042) decrease in incidence of hospital- acquired *C. difficile* acquisition. Application of the average incidence of *C. difficile* acquisition to the population of patients seen during the period of analysis, 0.48%, estimates 218 patients were expected to acquire *C. difficile* during the 19-month period. An increase in 1% hand hygiene performance equates to 3.6 prevented acquisitions of *C. difficile*. A single *C. dificilef* infection has been estimated to cost a hospital $6,000 - $9,000(Scott, 2009). Thus, for each 1% increase in HH performance, assuming an average cost of $7,500 per infection, $26,679 was saved in prevention of hospital-acquired *C. difficile*. In terms of yearly savings, a 1% increase in HH performance was estimated to prevent 2.2 infections annually, resulting in $16,850 savings each year. When considering a strict definition of MRSA acquisition as well as incidence of *C. difficile* acquisition, a 1% increase in hand hygiene performance can save a 600-bed hospital over $126,000 annually among patients at highest risk of acquisition.

The average hand hygiene rate in August 2014 was 34.4% across the medical center and had risen to an average 44.0% by February 2016, equating to an overall 9.6% absolute increase in average hand hygiene performance across the period of analysis. This increase, which was sustained above 40% for 6 months (Figure 4), resulted in an estimated prevention of 33 cases of hospital-acquired MRSA, using the strictest definition, saving $1,640,994 over the 19-month period. During this same timeframe, an estimated 34 cases of *C. difficile* infection were prevented, saving $256,118. In total, nearly $2 million were saved during the period of analysis associated with improvement in hand hygiene performance.

There are a number of limitations to this investigation. First, all estimations of patient characteristics were extrapolated from hospital encounters for which screening for MRSA colonization was completed. This may bias overall hospital characteristics towards the most acute patients cared for as active surveillance for colonization occurs only in intensive care units. However, the Poisson regression approach estimated the impact of these potential confounders on incidence of acquisition that was not affected by hand hygiene performance. Therefore, the relationship between hand hygiene and acquisition would not be affected by any bias introduced into the confounding variables such as age and Charlson index.

Next, cost savings estimations were based on overall improvements in hand hygiene performance, average patient characteristics such as length of stay, and estimated costs associated with infection previously reported in the literature. A more robust cost-benefit analysis may reveal greater detail about potential cost savings associated with hand hygiene.

Additionally, nasal swab and PCR testing is commonly recommended for detection of MRSA colonization, this approach does have limitations and cannot rule out colonization with MRSA in other areas of the body. MRSA transmission is known to have a seasonal effect with peaks in the summer and fall months. This seasonality was not accounted for in this analysis. The ability to incorporate APACHE scores or similar indices of patient acuity would be beneficial to this analysis as well. APACHE scores are not routinely assigned nor captured at this academic medical center.

Finally, a very low incidence of VRE prevented predictive power necessary to accurately explore the relationship between hand hygiene and this pathogen. While the sample size for a strict definition of MRSA acquisition was similarly low, the definition allowed for identification of truly hospital-acquired cases of MRSA, eliminating inclusion of persons entering the hospital carrying the organism or already infected by the organism from the outcome of interest. This is supported by the increased strength of association seen between HH and acquisition of MRSA when a strict definition requiring non-colonization status upon admission was used compared to the standard definition of diagnosis >48 hours after admission. Unlike this narrowed definition allowing for more accurate identification of hospital-acquired acquisition, the very small sample of VRE positive patients was defined by the standard definition of diagnosis >48 hours after admission. Thus, the outcome is likely to be contaminated by misclassification of patients who entered the hospital carrying the pathogen via colonization into the ‘acquisition’ outcome group. Therefore, future research assessing a strict definition of VRE with an increased sample size is recommended for accurate quantification of the relationship between hand hygiene and vancomycin-resistant enterococci.

vii. Conclusions

The impact of hand hygiene on prevention of hospital-acquired organisms is both clinically and statistically significant. Using hand hygiene surveillance data captured 24 hours a day, 7 days a week, every 1% increase in HH was seen to decrease incidence of MRSA in non-colonized patients by 4.4%. Similarly, each 1% increase in HH was seen to decrease incidence of by 1.6%. When considering a strict definition of MRSA acquisition as well as incidence of *C. difficile* acquisition, a 1% increase in hand hygiene performance can save a 600-bed hospital over $126,000 annually among patients at highest risk of acquisition. The introduction of HHMT into the healthcare setting allows for more robust assessment of the relationship between even the slightest increases in hand hygiene and healthcare-associated infections. Further research methods using time-series analysis may provide insight into these relationships while accounting for seasonal effects. However, these findings support continued dedication to improving hand hygiene in the healthcare setting.

V. EXECUTIVE SUMMARY

Healthcare-associated infections (HAI) are associated with extraordinary cost, both in terms of patient outcomes and hospital expenses. Approximately 1.7 million patients acquired a HAI in 2002 alone, accounting for approximately 99,000 deaths (Klevins et al., 2007). The economic impact of these infections has been estimated at $6.5 billion each year (Stone et al., 2005). Hand hygiene (HH) is widely believed to be the most effective modifiable factor for the prevention of HAIs (Whitby et al., 2007). Improved hand hygiene compliance has been associated with significant reduction in a plethora of healthcare-associated infections including overall HAI rates (Pittet et al., 2000), methicillin-resistant *Staphylococcus aureus* (MRSA) cross-contamination (Pittet et al., 2000), bacteremia (Grayson et al., 2008), and infection rates (Mestre et al., 2012), ventilator-associated pneumonia (VAP) (Al-Tawfig et al., 2013), central line-associated blood stream infection (CLA-BSI) (Al-Tawfig et al., 2013), and catheter-associated urinary tract infections (Al-Tawfig et al., 2013). A primary barrier to development of more rigorous interventions to improve hand hygiene is the lack of a reliable method to measure hand hygiene performance.

A number of hand hygiene monitoring technology (HHMT) options have become available on the commercial market, using technology such as Radiofrequency Identification (RFID) and Infrared Technology (IR) to measure both use of soap and alcohol-based hand rub (ABHR) as well as movement of healthcare personnel throughout a unit. However, a systematic review including 42 articles surrounding automated measuring systems found fewer than 20% of studies identified calculations for accuracy or efficacy of these systems (Ward et al., 2014). Of these, the level of rigor for assessment of system accuracy was variable. The purpose of this research was to assess the accuracy, acceptance, and impact of a Hand Hygiene Monitoring Technology (HHMT) to measure hand hygiene in an inpatient hospital setting.

Using a rigorous validation method, a HHMT providing unit-level hand hygiene performance was seen to have an overall sensitivity of 88.7% and positive predictive value of 99.2% when tested in a purposeful, controlled environment. When tested for accuracy in detecting behaviors in a real-world inpatient hospital setting, effectiveness of the HHMT was similarly high with overall system sensitivity increasing to 92.7% while PPV was 84.4%. While the HHMT was highly likely to detect room activity in a natural environment, reflected by high sensitivity, frequency of false positive events when measuring room activity was noteworthy-15.6% of all hand hygiene opportunities were false positives. These false positive events resulted in a deflated hand hygiene rate as the denominator of HH compliance was artificially inflated.

Reduced positive predictive value of the system in capturing room activity was associated with behaviors and workflows that resulted in frequent activity in or near room doorways. This has significant impact on interpretation of hand hygiene performance for healthcare providers working on units with high proportion of visitor activities. Lower positive predictive value of the system to detect room entries and exits means these units have an inflated denominator in reported hand hygiene performance. In other words, HH performance is underestimated by 10%-20% depending on the proportion of room activity attributed to visitors (Table XI). Ideally, HH performance presented to HCP on these units should be adjusted to reflect this underestimation, increasing reported compliance by 10% - 20%, depending on visitor activity. Similarly, expectations for target HH performance should be adjusted to account for this underestimation of compliance in order to improve the usefulness of this metric to healthcare personnel.

In addition to limited published data on the validity of these technologies, little exists on perceptions, acceptance, and utilization of these systems by healthcare personnel in the United States (Boyce, 2013). Using a survey tool rooted in the Theory of Planned Behavior, this study was the first known attempt to conceptualize healthcare personnel acceptance of hand hygiene monitoring technology using established social cognition theories as the underlying framework. In general, perceptions of the ease of using and the usefulness of the aggregate-level HHMT were moderately strong. Average perceived ease in using the technology was 8.6 (standard deviation: 2.3) on a 15-point scale; however, this composite variable was weakly interrelated. Average usefulness of the HHMT, which was a strongly interrelated construct, was 9.7 (standard deviation: 4.0) on an 18-point scale. In general, belief in the ability of oneself to contribute to hand hygiene performance as well as participation in collective hand hygiene performance by reminding others to perform HH were the most highly predictive characteristics of reported system usefulness and system use. These results support the existence of a relationship between perceived benefits of group hand hygiene performance and the perceived usefulness and reported use of a hand hygiene monitoring technology that measures hand hygiene at the unit level. Further research is needed to assess the strength of this relationship when applied to perceived benefits of individual hand hygiene and intention to use technologies to measure HH behaviors at the individual level. In order to improve perceived usefulness of the aggregate-level hand hygiene monitoring technology, efforts dedicated towards creating a culture that values hand hygiene not only at an individual level but also as a collective goal may prove beneficial.

Finally, using data collected from the hand hygiene monitoring technology, hospital operations, and the electronic medical record, this study found the impact of hand hygiene on prevention of hospital-acquired organisms to be both clinically and statistically significant. Using hand hygiene surveillance data captured 24 hours a day, 7 days a week, every 1% increase in HH was seen to decrease incidence of MRSA in non-colonized patients by 4.4%. Similarly, each 1% increase in HH was seen to decrease incidence of *C. difficile* by 1.6%. When considering a strict definition of MRSA acquisition as well as incidence of *C. difficile* acquisition, a 1% increase in hand hygiene performance can save a 600-bed hospital over $126,000 annually among patients at highest risk of acquisition. The introduction of HHMT into the healthcare setting allows for more robust assessment of the relationship between even the slightest increases in hand hygiene and healthcare-associated infections. Further research methods using time-series analysis may provide insight into these relationships while accounting for seasonal effects. However, these findings support continued dedication to improving hand hygiene in the healthcare setting.

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APPENDICES

APPENDIX A

Survey About Electronic Measuring of Hand Hygiene

You are being asked to participate in a research study. An aggregate electronic monitoring technology (the GOJO Smartlink System) has been installed throughout the UCM medical center. **We are asking you to complete the following survey in order to better understand user attitudes and perceptions of this technology to measure Hand Hygiene.**

Your participation in this survey is voluntary and will help to better understand the user experience of electronic methods to measuring Hand Hygiene. If you have any questions about this survey, please contact Heather Limper at hlimper@medicine.bsd.uchicago.edu. We value your opinion and appreciate your feedback. All responses are anonymous with the option to provide your email address for further participation. Your decision whether to participate will have no effect on your employment at University of Chicago.
Note: This survey is for research purposes and may not necessarily result in a change to the medical center's approach to data collection.

INSTRUCTIONS: Please answer the following questions and return to Heather Limper in S-152A (773-702-1479)

1. Which of the following best describes your job role? (Please circle one)

g. Attending
h. Environmental Services (EVS)
i. Food Services
j. Medical Student
k. Nurse Practitioner/ Physician's Assistant (ANP/PA)
l. Nursing Staff
a. Non-clinical Administrator
b. Patient Transportation
c. Physical Therapy/ Occupational Therapy
d. Physician trainee (Fellow, Resident, Intern)
e. Respiratory Therapy
f. Other ☐

2. What is your gender? ☐ Male ☐ Female

3. Do you own a smartphone? ☐ Yes ☐ No ☐ I don't know

3b. If yes, How often do you use Applications (Apps) on your smartphone?

☐ Never ☐ Occasionally ☐ Sometimes ☐ Always

4. How often do you work in clinical areas?

☐ Never ☐ Occasionally ☐ Sometimes ☐ Always

5. Which unit do you work on most frequently? ☐

(Example: 10North- MICU)

6. The unit I work on most frequently has installed the GOJO aggregate electronic system to measure hand hygiene.

☐ Yes ☐ No ☐ I don't know

7. Which best describes your experience with hand hygiene monitoring technology:

☐ Not At All Familiar ☐ Not Very Familiar ☐ Somewhat Familiar ☐ Very Familiar

8. I feel that I can contribute to improving hand hygiene performance

☐ Strongly Do Not Agree ☐ Do Not Agree ☐ Agree ☐ Strongly Agree

9. How accurate do you feel the GOJO system is at capturing hand hygiene behavior?

☐ Not At All Accurate ☐ Not Very Accurate ☐ Somewhat Accurate ☐ Very Accurate

BACK ------>

APPENDIX A (continued)

Please answer the questions below about your feelings towards and interactions with the GOJO aggregate electronic monitoring technology to measure Hand Hygiene. If your area has not installed this system, please answer based on your intentions to interact with the technology. *Remember, there are no right or wrong answers, it is only important to choose the best answer that reflects your feelings and experience.*

Please select the best answer.	Never	Occasionally	Sometimes	Always
I pay attention to the red/green lights on the activity counters above room doors				
I look at hand hygiene performance on the monitor located at the nurses station				
I use the monitoring system to track hand hygiene behavior				
I discuss hand hygiene performance at staff huddles				
I am reminded to perform hand hygiene by others				
I remind others to perform hand hygiene				

Please select the best answer.	Strongly Do Not Agree	Do Not Agree	Agree	Strongly Agree
I find the GOJO system useful in my job				
I understand how my interaction with the GOJO system impacts HH performance				
I sometimes find it difficult to use the GOJO system				
I sometimes find my interaction with the GOJO system to be unclear				
I find it easy to get information from the GOJO system				
I sometimes find the GOJO system hard to understand				

Please select the best answer.	Strongly Do Not Agree	Do Not Agree	Agree	Strongly Agree
The GOJO system promotes hand hygiene as a priority				
The GOJO system accurately measures hand hygiene performance.				
I believe the GOJO system is a good approach to **measuring** hand hygiene				
I believe the GOJO system is a good approach to **improving** hand hygiene				
The GOJO system is useful for understanding hand hygiene performance.				

COMMENTS *(optional):*

I am interested in further helping investigators understand user experience with the GOJO system. Please contact me. *(Optional)* Name:

Email: Phone:

APPENDIX B

Exploration of impact of GOJO Smartlink™ technology on incidence of HA-MRSA

The application of interrupted-time series analysis to the relationship between hand hygiene performance and incidence of HA-MRSA is shown in Figure 7. The first intervention represents installation of the GOJO SMARTLINK™ technology. The linear trend of this intervention was non-statistically significant (linear trend: 8, Coef: 0.0003, p= 0.700). The second intervention represents a medical-center wide initiative to promote 100% compliance with hand hygiene policy. The linear trend of this campaign was statistically significant (linear trend: 24, Coef: 0.0023, p= 0.006) although there were not enough observations during this time period for interpretation. These findings support a non-statistically significant impact of a change in measurement approaches toward hand hygiene on the relationship between hand hygiene and HA-MRSA prevention, which is anticipated.

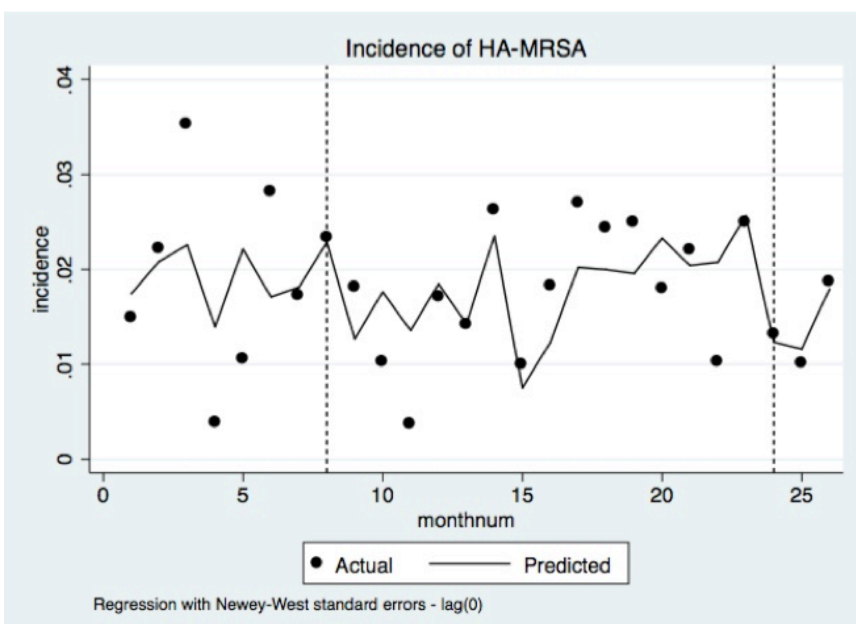


Figure 7. Interrupted time series analysis displaying HH and incidence of HA-MRSA
*Intervention 1: Introduction of GOJO SMARTLINK™ technology
*Intervention 2: Hospital-wide hand hygiene promotion campaign

APPENDIX C

Trends in hand hygiene and HAI acquisition over time

Trends in hand hygiene performance and acquisition of MRSA among non-colonized individuals, *C. difficile* infection, and VRE infection are displayed in Figure 8. The relationship between hand hygiene performance and infection acquisition does not show evidence of being influenced by time. Specifically, general trends upward in hand hygiene show lower incidence of infection. This supports the use of Poisson regression for this analysis rather than time-series analysis. However, future application of time-series analysis to explore seasonality may prove beneficial.

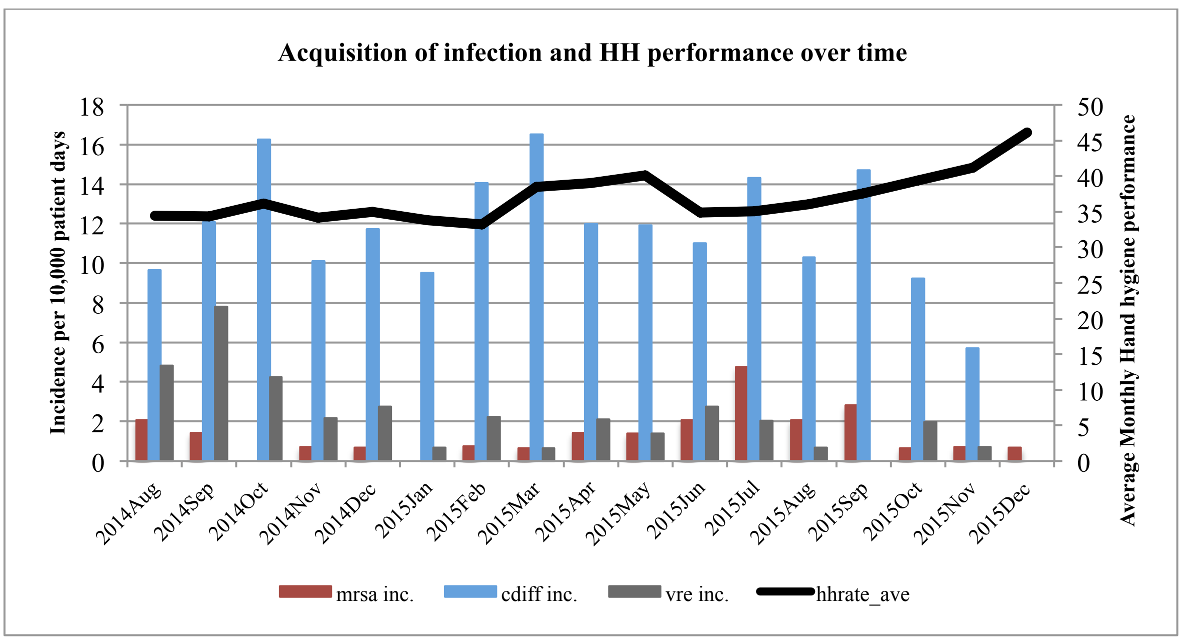


Figure 8. Trends of HH performance and HAIs over time

APPENDIX D

IRB and Determination of quality improvement status

Determination of Quality Improvement Application

Process for Determining Quality Improvement vs. Human Subjects Research

Revised 07/29/2015

Name:	Heather M Limper
Email:	hlimper@medicine.bsd.uchicago.edu
Project Title:	Validation of electronic monitoring system to measure hand hygiene

Project description (detailed enough to understand the major points of the project):

We aim to validate the GoJo Smartlink system to quantify accuracy compared to direct observation and video surveillance monitoring using security cameras accessible only through a secure computer in infection control. No identifiable information will be recorded during these processes, capturing only # of hand hygiene events and # of room entries and exits. When possible, status of a person as a "employee", "visitor", "patient," or "EVS worker" may be recorded to quantify the number of hand hygiene opportunities attributable to healthcare providers at UCM.

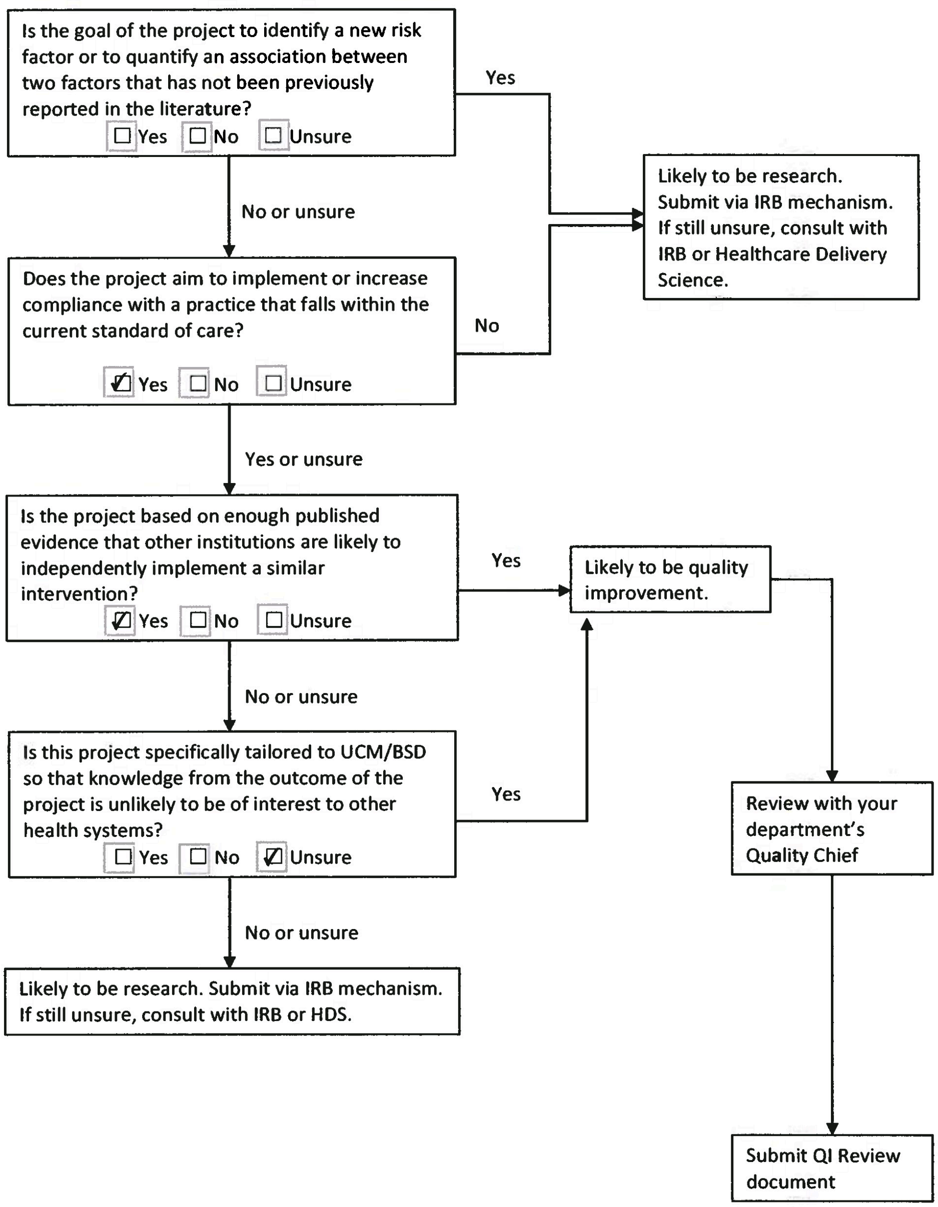
Describe why you believe this project is quality improvement and not human subjects research:

This project is necessary to ensure accuracy of our approach to measuring hand hygiene performance throughout the hospital using the GoJo Smartlink system and to verify allocation of resources towards this technology is appropriate. Hand hygiene is an evidence based approach to preventing the spread of infection and appropriate ways to measure this behavior is necessary to progress in improving this behavior to improve patient safety.

If you could not disseminate these results outside of UCM/BSD, would you conduct the work? How would it differ from what you plan now?

Yes. It would not differ at all.

Complete the following flow chart (yes/no boxes are clickable):



Answer the following by initialing in the appropriate spots:

The goal of this project is to improve care. All patients will receive the standard of care	[✓] Agree	[ ] Disagree
This project involves implementing care practices that are evidence- or consensus-based. It does not test an intervention that is beyond current science and experience.	[✓] Agree	[ ] Disagree
If publishing or presenting your work, you are comfortable with the following statements in your methods section: "This project received a formal Determination of Quality Improvement status according to University of Chicago Medicine institutional policy. As such, this initiative was deemed not human subjects research and was therefore not reviewed by the Institutional Review Board."	[✓] Agree	[ ] Disagree

Attestations:

- I have provided correct, accurate, and truthful information above.
- As the project leader, I have completed the institution's required Human Subjects Research training (i.e. CITI program, NIH training).
- If I have any further questions, I will reach out to the IRB and/or to Healthcare Delivery Science.
- In all cases, I will follow institutional guidelines for information security and HIPAA guidelines. If I do not understand them, I will reach out to the HIPAA office and to the office of the Chief Information Security Officer for clarification.
- I understand that this process does not provide approval for resources to perform quality improvement projects or data extraction.
- I attest that I have read this policy in its entirety.
- I agree to resubmit my project to this process should the procedures change.

Heather M Limper Digitally signed by Heather M Limper Date: 2015.11.01 13:33:15 -06'00'

Project Leader

November 1, 2015

Date

Approvals

Department Quality Chief Approval

Quality Chief Comments:

I have reviewed this project and agree that it represents quality improvement, not human subjects research.

______________________________ ________________

Department Quality Chief Date

Associate Chief Medical Officer for Clinical Quality (or Clinical Effectiveness Designee)

Comments: Please see formal email notification for details.

I have reviewed this project and agree that it represents ~~quality~~ improvement, not research.

______________________________ 12/16/2015

Associate CMO or Designee Date

Date of approval

Monday, March 7, 2016 at 10:20:23 AM Central Standard Time

Subject: AURA IRB: IRB15-1482 Notification of Expedited Approval - Survey of EMS Attitudes
Date: Monday, March 7, 2016 at 10:18:33 AM Central Standard Time
From: _aura-irb@uchicago.edu
To: heatherl@uchicago.edu

AURA THE UNIVERSITY OF CHICAGO

BSD IRB
The University of Chicago Biological Sciences Division/University of Chicago Medical Center
5751 S. Woodlawn Ave., 2nd floor, Chicago, IL 60637
FWA00005565

Notification of Expedited Approval

Date of Letter:	3/7/2016
Protocol Number/Submission Link:	IRB15-1482
Type of Submission:	New Study
Status:	**Approved**
Principal Investigator:	Emily Landon
Protocol Title:	Survey assessment: Attitudes around electronic measuring of hand hygiene
Risk Level:	Minimal Risk
Consent Type:	Waiver of Documentation of Consent
Authorization Type:	Requesting waiver/alteration of authorization, including oral consent
Vulnerable Populations:	None
Funding:	Internally Funded
Protocol Version:	IRB15-1482 revisions_clean.docx NRC Review Letter 2016-2-23.pdf Signed critical care review form_NRC Study Protocol
Stamped Documents:	Email and website language.docx.pdf Phase 1 Consent Script.pdf Phase 2 Consent Script.pdf
Approval Date:	3/7/2016

The above-referenced study was approved by the IRB. The expiration date of this study is 3/6/2017 .

Stamped approved documents associated with this study can be found in the study workspace, by following the Submission Link above.

If you need assistance, please contact the IRB from the submission workspace by clicking the “Send Email to IRB Team” activity.

THE UNIVERSITY OF CHICAGO MEDICINE

February 23, 2016

Dear Ms. Limper,

The University of Chicago Medicine Nursing Research Council is pleased to inform you that your research proposal *Assessment of an aggregate electronic monitoring system to measure hand hygiene in a hospital setting* has been accepted. After careful review, your proposal satisfactorily addresses the aspects required for the committee's approval. The council did have some comments for your consideration for the study-however, these actions are not required.

If you have not yet done so, you may submit your proposal to the University of Chicago Institutional Review Board (IRB). Please visit http://aura.uchicago.edu/ to complete the IRB submission. Please be sure to indicate that Nursing Research Committee review is required for your proposal in AURA under section 2.1 Research Categories "Required Additional Reviews." This will allow us to communicate approval of your study to the IRB.

If you have questions or would like further assistance, please contact Cynthia LaFond PhD, RN, CCRN-K, Director for Nursing Research.

We wish you continued success in your research endeavors.

Thank you,

The University of Chicago Nursing Research Council

Co-chairs:
Cynthia M. LaFond PhD, RN, CCRN
Mark Lockwood MSN, RN, CCRC

UNIVERSITY OF ILLINOIS
AT CHICAGO

Office for the Protection of Research Subjects (OPRS)
Office of the Vice Chancellor for Research (MC 672)
203 Administrative Office Building
1737 West Polk Street
Chicago, Illinois 60612-7227

Approval Notice
Initial Review – Expedited Review

March 23, 2016

Heather Marie Limper, MPH
Epidemiology and Biostatistics
1603 W. Taylor
987 SPHPI, M/C 923
Chicago, IL 60612
Phone: (312) 520-2451

RE: Protocol # 2016-0319
"Assessment of an Aggregate Electronic Monitoring System To Measure Hand Hygiene In a Hospital Setting"

Dear Ms. Limper:

Members of Institutional Review Board (IRB) #1 reviewed and approved your research protocol under expedited review procedures [45 CFR 46.110(b)(1)] on March 23, 2016. You may now begin your research

Your research meets the requirement(s) for the following category - Expedited Review Approval Category 45 CFR 46.110(b)(1):

Protocol reviewed under expedited review procedures [45 CFR 46.110] Category: 5, 7

(5) Research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for nonresearch purposes (such as medical treatment or diagnosis).,
(7) Research on individual or group characteristics or behavior (including but not limited to research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

Please note the following information about your approved research protocol:

Protocol Approval Period: March 23, 2016 - March 23, 2017

Approved Subject Enrollment #: 400
Additional Determinations for Research Involving Minors: These determinations have not been made for this study since it has not been approved for enrollment of minors.
Performance Sites: UIC, University of Chicago
Sponsor: None
Research Protocol(s):

a) Attitudes around electronic measuring of hand hygiene [University of Chicago PI, Emily Landon –as submitted on 3/21/2016]

Recruitment Material(s):

a) All research activities including enrollment, consent, recruitment, survey collection are occurring at University of Chicago. Documents do not need to be stamped by UIC IRB.

Informed Consent(s):

a) Waiver of Signed Consent Document granted [45 CFR 46.117(c)(i)]
b) All research activities including enrollment, consent, recruitment, survey collection are occurring at University of Chicago. Documents do not need to be stamped by UIC IRB.

Please note the Review History of this submission:

Receipt Date	Submission Type	Review Process	Review Date	Review Action
03/21/2016	Initial Review	Expedited	03/23/2016	Approved

Please remember to:

à **Use only the IRB-approved and stamped consent document(s) enclosed with this letter when enrolling new subjects.**

☾ Use your **research protocol number** (2016-0319) on any documents or correspondence with the IRB concerning your research protocol.

à Review and comply with all requirements on the enclosure,
"UIC Investigator Responsibilities, Protection of Human Research Subjects"
(*http://tigger.uic.edu/depts/ovcr/research/protocolreview/irb/policies/0924.pdf*)

Please note that the UIC IRB has the right to ask further questions, seek additional information, or monitor the conduct of your research and the consent process.

Please be aware that if the scope of work in the grant/project changes, the protocol must be amended and approved by the UIC IRB before the initiation of the change.

We wish you the best as you conduct your research. If you have any questions or need further help, please contact the OPRS office at (312) 996-1711 or me at (312) 413-9680. Please send any correspondence about this protocol to OPRS at 203 AOB, M/C 672.

Sincerely,

Jovana Ljuboje
IRB Coordinator, IRB #1
Office for the Protection of Research
Subjects

cc: Ronald C. Hershow, Faculty Sponsor, M/C 922
Ronald C. Hershow, Epidemiology and Biostatistics, M/C 923

Determination of Quality Improvement Application

Process for Determining Quality Improvement vs. Human Subjects Research

Revised 07/29/2015

Name:	Heather M Limper
Email:	hlimper@medicine.bsd.uchicago.edu
Project Title:	Impact of hand hygiene performance on reduction of transmissible pathogens in the ICU

Project description (detailed enough to understand the major points of the project):

We propose to use an aggregate electronic monitoring system (GoJo Smartlink System) capable of measuring hand hygiene performance 24 hours a day, 7 days a week, to assess the impact of hand hygiene point prevalence of a number of transmissible pathogens including MRSA, VRE, and all HAIs. We intend to quantify the impact of efforts to improve HH on patient safety in the adult ICU setting, where most HH improvement efforts have focused.

Describe why you believe this project is quality improvement and not human subjects research:

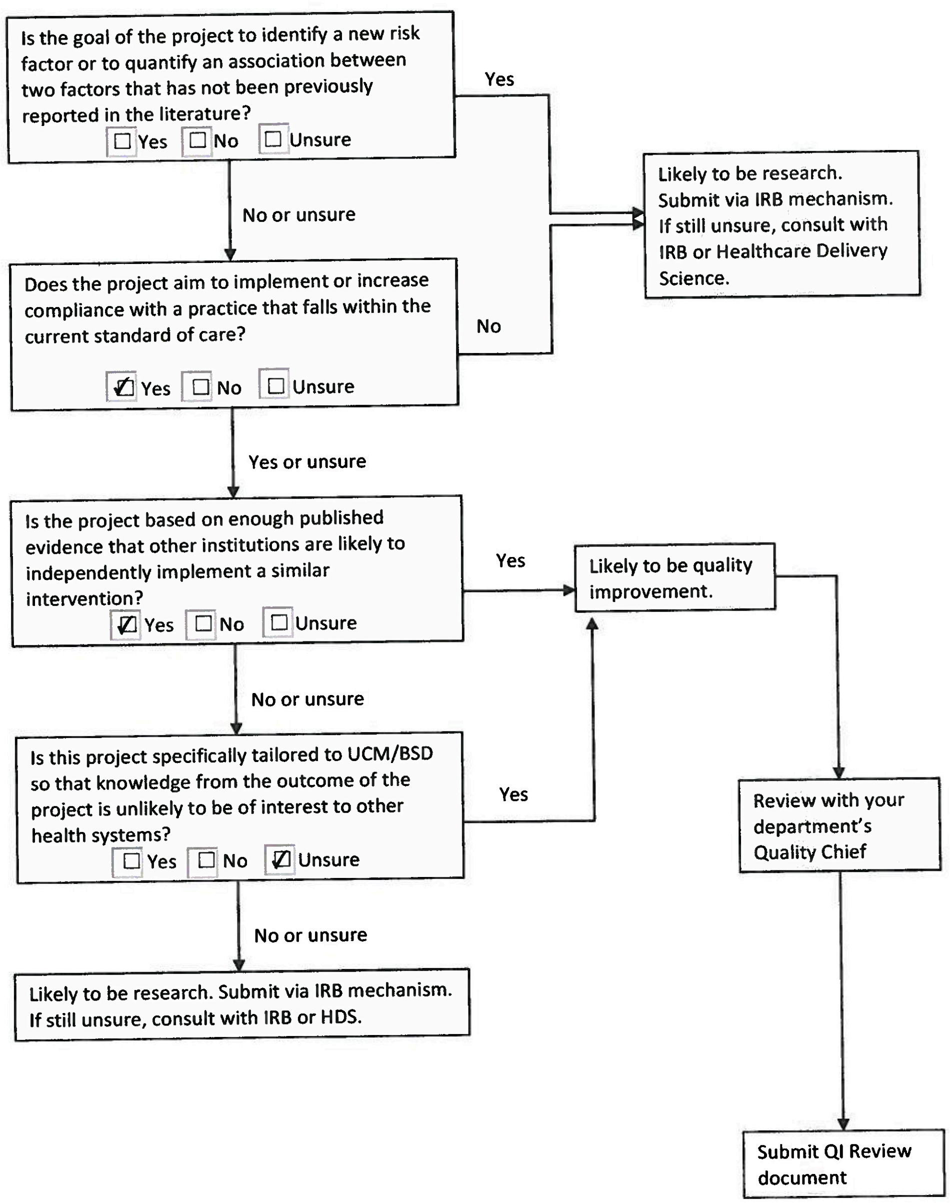
Hand washing has been known to be a successful infection control strategy since it was first shown by Ignaz Semmelweis to reduce the incidence of puerperal fever in women during labor in 1847.11 Since then, a large body of evidence has accumulated showing a temporal association between improved hand hygiene compliance and significant reduction in a plethora of healthcare associated infections including overall HAI rates12, methicillin-resistant Staphylococcus aureus (MRSA) cross-contamination12, bacteremia13, and infection rates14, ventilator-associated pneumonia (VAP)15, central line-associated blood stream infection (CLA-BSI)15, and catheter-associated urinary tract infections.15

We aim to quantify the impact of hand hygiene, measured using 24/7 electronic monitoring technology, on healthcare-associated infection acquisition in the adult ICU setting at University of Chicago Medicine. HH and infection rates will be analyzed from 6 adult ICUS (MICU, SICU, CICU, D2, Stem Cell Transplant Unit, NeuroICU) providing over 60 patient beds.

If you could not disseminate these results outside of UCM/BSD, would you conduct the work? How would it differ from what you plan now?

Yes. If we could not disseminate the results outside of UCM/BSD the difference from the current proposal would be limited to our intended audience.

Complete the following flow chart (yes/no boxes are clickable):



Answer the following by initialing in the appropriate spots:

The goal of this project is to improve care. All patients will receive the standard of care	[✓] Agree	[ ] Disagree
This project involves implementing care practices that are evidence- or consensus-based. It does not test an intervention that is beyond current science and experience.	[✓] Agree	[ ] Disagree
If publishing or presenting your work, you are comfortable with the following statements in your methods section: "This project received a formal Determination of Quality Improvement status according to University of Chicago Medicine institutional policy. As such, this initiative was deemed not human subjects research and was therefore not reviewed by the Institutional Review Board."	[✓] Agree	[ ] Disagree

Attestations:

- I have provided correct, accurate, and truthful information above.
- As the project leader, I have completed the institution's required Human Subjects Research training (i.e. CITI program, NIH training).
- If I have any further questions, I will reach out to the IRB and/or to Healthcare Delivery Science.
- In all cases, I will follow institutional guidelines for information security and HIPAA guidelines. If I do not understand them, I will reach out to the HIPAA office and to the office of the Chief Information Security Officer for clarification.
- I understand that this process does not provide approval for resources to perform quality improvement projects or data extraction.
- I attest that I have read this policy in its entirety.
- I agree to resubmit my project to this process should the procedures change.

Heather M Limper Digitally signed by Heather M Limper Date: 2015.11.01 13:40:29 -06'00'

Project Leader

November 1, 2015

Date

Approvals

Department Quality Chief Approval

Quality Chief Comments:

I have reviewed this project and agree that it represents quality improvement, not human subjects research.

Department Quality Chief

Date

Associate Chief Medical Officer for Clinical Quality (or Clinical Effectiveness Designee)

Comments: Please see formal email notification for details

I have reviewed this project and agree that it represents quality improvement, not research.

Associate CMO or Designee

12/16/2015

Date

Date of approval

16 Dec 2015

RE: Determination of Quality Improvement Status

Dear Heather:

I reviewed the description of your projects, focused on improving hand hygiene via electronic measurement and impact on infections. In my opinion, under University of Chicago Medicine's standards, this represents quality improvement, rather than human subjects research, because

- Your project's goal is to improve clinical care based on accepted standards and evidence-based practice.
- It follows evidence-based, well-supported guidelines.
- It uses generally accepted, locally specific quality improvement processes to improve care.
- Although you will analyze data to understand whether the change resulted in an improvement, this is an integral part of modern quality improvement practice (and in fact, good QI cannot be conducted without assessing its impact).
- It provides the basis for multiple small tests of change that are contextually dependent (the 'P' in PDSA cycles).

In addition, because I have been involved in the hand hygiene work, for this review I served in the role of 'QI Chief,' and asked Krista Curell, RN Esq, to provide a second level of review in her role as Vice President, Risk Management and Patient Safety. We discussed these projects in person today, and she agrees that they represent quality improvement and patient safety improvement work, not human subjects research.

Please note that we do advocate for publishing quality improvement project evaluations, and that the generally accepted approach is to follow the SQUIRE Guidelines (http://www.squire-statement.org/guidelines).

While this assessment does not determine resource allocation (e.g. for data acquisition), it does serve as a formal institutional determination of quality improvement status. Please save this email as a record of formal assessment of QI status. You may use the following language (for example, in the Methods section of a manuscript) if you choose to share your results outside of the institution:
'This project was formally determined to be quality improvement, not human subjects research, and was therefore not overseen by the Institutional Review Board, per institutional policy.'

Thank you,
Michael D. Howell, MD MPH
Chief Quality Officer
University of Chicago Medicine

VITA

Heather M. Limper, MPH

Education:

University of Georgia, Athens, Georgia, Bachelor of Science, Biology 2004 – 2008

University of Illinois at Chicago, Chicago, Illinois 2008 - 2010
Master of Public Health, Epidemiology
Capstone passed with honors

University of Chicago, Chicago, Illinois 2010 - 2011
Certificate in Medical Writing and Editing

Academic Appointments:

Adjunct Laboratory Instructor, School of Medicine, Northwestern University 2010 - 2012
Instructor, School of Liberal and Professional Studies, University of Chicago 2015 - 2016

Ph.D.-Granting Committee, Program, Institute, and Center Appointments
Center for Healthcare Delivery Science, University of Chicago Medicine 2014 – 2016

Hospital Appointments:

Research Project Coordinator, Infection Control Program, University of Chicago 2009 - 2010
Program Director, Health4Chicago, Department of Pediatrics 2010 - 2014
University of Chicago
Coordinator of Scholarly Activity, Office of Clinical Effectiveness 2012 - 2014
University of Chicago Medicine
Epidemiologist, Center for Healthcare Delivery Science and Innovation 2014 - 2016
University of Chicago Medicine

Employment:

Graduate Research Assistant, Department of Pediatrics 2014 - 2016
University of Illinois at Chicago
Graduate Teaching Assistant, School of Public Health 2012 - 2013
University of Illinois at Chicago
Rotating Lecturer, Department of Medicine, University of Chicago 2011 - 2013
HPV Project Sub-contractor 2014
American Academy of Pediatrics
Chicago Department of Public Health
Health Educator, First Steps Athens Area Child Abuse Prevention Council 2005 - 2008

Professional Organizations:

American Medical Student Association, Community Outreach Founder University of Georgia Chapter	2005 - 2007
American Medical Student Association, President Elect University of Georgia Chapter	2007 - 2008
Public Health Student Association, Vice President Elect University of Illinois at Chicago Chapter	2009 - 2010
American College of Epidemiology, Associate Executive Member	2010 -
American Public Health Association	2010 - 2012
Society for Epidemiologic Research	2010 - 2014
American Academy of Pediatrics, Illinois Chapter Member	2010 - 2015
Medical Reserve Corp, Chicago Department of Public Health, Volunteer	2011 - 2016
AcademyHealth Student Member	2014 - 2016

Professional Activities:

Intramural:

Academic Strategic Planning Committee, Student Member Elect University of Illinois at Chicago	2009 - 2010
Recurrent Ad-hoc Member, Medical Center Quality Committee University of Chicago Medicine	2013 - 2014
Member, Committee on Infection Control and Epidemiology University of Chicago Medicine	2014 - 2016
Member, Pediatric Quality Committee University of Chicago Comer Children's Hospital	2014 - 2016
Scholarship Lead, Hand Hygiene Leadership Committee University of Chicago Medicine	2014 - 2016
Planning Lead, Quality & Safety Symposium, University of Chicago Medicine	2014 - 2016
Reviewer, Quality & Safety Symposium Poster session, University of Chicago	2014 - 2016
Reviewer, 100,000 Innovations Grant Program, University of Chicago Medicine	2014 - 2016
Medical Center Quality Committee, University of Chicago Medicine	2014 - 2016
Reviewer, Hand Hygiene Slogan Competition, University of Chicago Medicine	2015
Analytics Core, University of Chicago	2015 - 2016
Making A Difference Every Day Best Practice Forum Committee, Univ of Chicago	2015 - 2016
Seated Voting Member, Institutional Review Board, Committee A University of Chicago Biological Sciences Division	2015 - 2016
MOC Sponsorship Program Committee, University of Chicago	2015 - 2016
Continuing Professional Development Task Force, University of Chicago	2015 - 2016
Advisory Council for Medical Writing and Editing Certificate Program Graham School for Liberal and Professional Studies University of Chicago	2015 - 2016
Committee for Continuing Professional Development University of Chicago Medicine	2016

Extramural:

National Journal Club Leader, American College of Epidemiology,	2010 - 2012
HPV Advisory Committee, Chicago Department of Public Health	2013 - 2016
Grant Review Board, Housing Opportunities for Persons with AIDS Chicago Department of Public Health	2014
Review Board, Interdisciplinary Undergraduate Research Journal University of Illinois at Chicago	2014 - 2015
Review Board, American Journal of Health Behavior	2014 -
Review Board, Postgraduate Medical Journal, British Medical Journal	2014 -
Review Board, Community Health Planning and Policy Development National Conference, American Public Health Association	2014 -
Review Board, Multi-Specialty MOC Portfolio Approval Program American Board of Medical Specialties	2015 -
Co-Lead, Teaching Corner, Annals of Epidemiology	2015 -

Special Awards or Recognition for Professional Activities**:**

Phi Eta Sigma National Honors Society	2005 - 2008
National Society of Collegiate Scholars Lifetime Member	2005
National Dean's List for Academic Honors	2005
Honored Employee, Athens Area Child Abuse Prevention Council	2007
Honorary Installation Engineer, Proventix	2010
Employee of the Month, December, Comer Children's Hospital University of Chicago Medicine	2011
Scholarship Winner, American College of Epidemiology Policy Conference	2011
Chancellor's Student Service Award, University of Illinois at Chicago	2013
Healthy Chicago Award to Health4Chicago, Chicago Department of Public Health	2013
Recognition Award, Contributions to Healthcare Delivery Science Research, UCM	2016

Teaching Activities:

Graduate School Courses:

Introduction to Epidemiology Laboratory (EB 301), 24 lectures	2010 - 2012
Intermediate Epidemiology Laboratory (EB 401), 24 lectures	2010 - 2012
Advanced Epidemiology Laboratory (EB 501), 12 lectures	2010 - 2012
Outbreak Investigation (EPID 490), 12 lectures	2012
Public Health Surveillance (EPID 490), 12 lectures	2013
Health Analytics (MscA 23006), 10 lectures, Curriculum Development	2015 - 2016

Continuing Medical Education:

Clinical Effectiveness Journal Club, Organizer and Lecturer	2014 - 2016
Infection Prevention and Control: The School Setting, Organizer and Lecturer	2014 - 2016

Research Supervision

Washell Holmes, BS Candidate Chicago State University — 2013

Immunization health education development targeting parents on Chicago's South Side

Alice-Grey Lewis, BS Candidate Honors College, University of Illinois at Chicago — 2013 - 2014

Parental declination of school-located vaccination services

Annie Boesen, MPH Candidate, Health Policy, University of Illinois at Chicago 2013 - 2014
HPV adolescent consent policies and implications for vaccine uptake

Molly Davisson, Clinical Nurse Leader Candidate, Rush University 2013 - 2014
Reaching Our Goals: Education of primary care nursing staff to improve adolescent immunization rates

Elizabeth Danielson, Prospective doctoral student, Indiana University 2014 - 2015
Homogeneity of bacteria in tracheostomies and the implication for contact precautions in a pediatric specialty care hospital

Shuyang Yu, Erikson Fellow, MHA Candidate, University of Chicago 2015
360 degree Experience in Operational Problem Solving

Maura Foley, Melissa Villa, Shelby Bridges, MscA Candidates, Capstone Advisor 2015
University of Chicago, Best-in-Show Capstone Winners
Identifying High Risk Patients for the Comprehensive Care Physician Model

Research Program:

School-based Immunization: A Unified Immunization Consent and Health Promotion Letter, The Women's Board, University of Chicago, $9,000 2013

Publications and Presentations:

Articles in Refereed Journals:

1. Appel LJ, Angell SY, Cobb LK, **Limper HM**, Nelson DE, Samet JM, Brownson RC. *Population-Wide Sodium Reduction: The Bumpy Road from Evidence to Policy.* Ann Epidemiol. 2012 Jun;22(6):417-25. doi:10.1016/j.annepidem.2012.04.003.
2. **Limper HM,** Barton G, McGinty M, Landon E, O'Boyle C, Reddy S, Weber SG. *Behavioral intention of physician trainees and medical students to practice hand hygiene.* Infect Control Hosp Epidemiol. 2013 Oct;34(10):1102-5. doi: 10.1086/673146.
3. Pineles LL, Morgan DJ, **Limper HM**, Weber SG, Thom KA, Perencevich EN, Harris AD, Landon EM. *Accuracy of a radiofrequency identification badge (RFID) system to monitor hand hygiene behavior during routine clinical activities.* American Journal of Infection Control. 2013 Dec 17. doi: 10.1016/j.ajic.2013.07.014.
4. **Limper HM**, Burns JL, Lloyd LM, Atilano J, Alexander KA, Caskey RN. *Challenges to School-located Vaccination: Lessons Learned.* Pediatrics. 2014 Sept 15. doi: 10.1542/peds.2014-1339
5. **Limper HM**, Lewis AG, Alexander KA, Caskey RN. *Parental Declination of School-Located Vaccination Services.* Ann Vaccines Immunization 2014. 1(2):1008.
6. **Limper HM**, Burns JL, Alexander KA. *Taxi Drivers: A Target Population For The Prevention of Transmissible Disease?* J Community Health. April 2016. 41(2):207-210. doi: 10.1007/s10900-015-0099-9.
7. **Limper HM**, Caskey RN. *Medicaid Managed Care: Unanswered Impact on School-Located Immunization Services.* NASN Sch Nurse. 2016 Apr 1.
8. Tothy A, **Limper HM**, Droscoll J, Bittick N, Howell MD. *The Ask Me To Explain Campaign: A 90-Day Intervention to Promote Patient and Family Involvement in Care in a Pediatric Emergency Department.* Jt Comm J Qual Patient Saf. 2016 Jun;42(6):281-6.

9. **Limper HM**, Garcia-Houchins S, Slawsky L, Hershow RC, Landon E. *A Validation Protocol: Assessing the Accuracy of Hand Hygiene Monitoring Technology.* Infect Control Hosp Epidemiol. *In press.*

Abstracts:

1. Martha Baggetto, **Heather M. Limper**, Jennifer Burns, Kenneth Alexander, Emily Mawdsley, Stephen G. Weber. *Infection Prevention and Control in the School Setting: A Grass-Roots Collaboration.* Comer Children's Hospital Pediatric Research Day. Chicago, IL. May 2011.
2. Martha Baggetto, **Heather M. Limper**, Jennifer Burns, Kenneth Alexander, Emily Mawdsley, Stephen G. Weber. *Infection Prevention and Control in the School Setting: A Grass-Roots Collaboration.* National Association of School Nurses National Conference. Washington, DC. June 2011.
3. Emily Mawdsley, **Heather M. Limper**, Pamela McCall, Corrin Steinhauer, Bruce Minskey, Stephen G. Weber. A novel motivational method for improving hand hygiene compliance among healthcare providers. Society for Healthcare Epidemiology of America National Conference. Dallas, TX. April 2011.
4. Emily Mawdsley, **Heather M. Limper**, Lisa Pineles, Stephen G. Weber, Daniel Morgan. Radiofrequency identification as a method for improving hand hygiene compliance among healthcare providers. Infectious Disease Society of America International Conference. Boston, MA. October 2011.
5. Jennifer Burns, Maria Newark, Kenneth A. Alexander, Melody Altman, **Heather M. Limper.** *School-based immunization: Increasing vaccine uptake in the school community.* Comer Children's Hospital Pediatric Research Day. Chicago, IL. May 2012.
6. Jennifer Burns, Maria Newark, Kenneth A. Alexander, Melody Altman, **Heather M. Limper.** *School-based immunization: Increasing vaccine uptake in the school community.* National Association of School Nurses National Conference. San Francisco, CA. June 2012.
7. Jennifer Burns, Alison H. Bartlett, Martha Baggetto, Kenneth A. Alexander, Stephen G. Weber, **Heather M. Limper**. *Infection Prevention and Control in the School Setting: A Grass Roots Collaboration Update.* National Association of School Nurses National Conference. San Francisco, CA. June 2012.
8. **Heather M. Limper**, Grant Barton, Michael McGinty, Emily Landon, Shalini Reddy, Stephen G. Weber. *Knowledge, Attitudes, and Beliefs: Looking at Hand Hygiene Through The Theory of Planned Behavior.* ID Week. San Diego, CA. October 2012.
9. **Heather M. Limper**, Jennifer Burns, Jenny Atilano, LaKesha Lloyd, Rachel Caskey, Ken Alexander. *Health4Chicago: Increasing Adolescent Immunization at Schools.* Comer Children's Hospital Pediatric Research Day. Chicago, IL. May 2013.
10. Gomez A, **Limper HM**, Landon E. *Healthcare Providers' Motivations for Hand Hygiene Compliance.* IDWeek. San Francisco, CA. October 2013
11. Rojas JC, **Limper HM**, Charnot-Katskas A. *Expectations for Turn-Around Times in Inpatient Phlebotomy Services.* University of Chicago Medicine's annual Quality & Safety Symposium. Chicago, IL. May 2014.

12. Turner P, Weekly K, **Limper HM**, Curell K. *Risk Management and Patient Safety: Informed Policies to Prevent Retained Foreign Objects.* University of Chicago Medicine's annual Quality & Safety Symposium. Chicago, IL. May 2014.
13. **Limper HM**, Bartlett AH. *Knowledge, Attitudes, and Beliefs around Infection Control Best Practices Among Physician Trainees.* University of Chicago Medicine's annual Quality & Safety Symposium. Chicago, IL. May 2014.
14. **Limper HM**, Perez C, Siminski Tom, Bartlett AH. *Are You Gel-in? A Hand Hygiene Pledge Campaign on the PICU.* University of Chicago Medicine's annual Quality & Safety Symposium. Chicago, IL. May 2014.
15. Burns J, **Limper HM**, Walsh L, Jones K, Davis S, Acree E, Nash C, Bhatti M, Johnson D, Alexander K. *Health Behaviors and Choices of Patients at Comer Family Flu Clinic.* Comer Children's Hospital Pediatric Research Day. Chicago, IL. May 2014.
16. Burns J, **Limper HM**, Walsh L, Neer M, Caskey RN, Wildman L, Alexander K. *Innovation in Travel Medicine: Provision of comprehensive travel medicine at a School-Located Vaccination Clinic*. Wilderness Medical Society Annual Meeting. Jackson Hole, WY. August 2014.
17. Holmes A, Weeks K, Turner P, **Limper HM**, Schmitz A, Whelan C, Curell K. *Informed Policies To Prevent Retained Foreign Objects.* Institute for Healthcare Improvement 26th Annual National Forum. Orlando, FL. December 2014.
18. University of Chicago Medicine's **Hand Hygiene Leadership Committee**. *Applying Lean Principles to Identify Barriers to Hand Hygiene.* Institute for Healthcare Improvement 26th Annual National Forum. Orlando, FL. December 2014.
19. University of Chicago Medicine's **Hand Hygiene Leadership Committee**. *Validation of the GoJo Smartlink System For Electronic Monitoring of Hand Hygiene.* University of Chicago Medicine's Quality & Safety Symposium. May 2015.
20. University of Chicago Medicine's **Hand Hygiene Leadership Committee**. *Applying Lean Principles to Identify Barriers to Hand Hygiene.* University of Chicago Medicine's Quality & Safety Symposium. May 2015.
21. Ruokis S, **Limper HM** Marrs R, Garcia-Houchins S, Landon E. *Applying Lean Principles to Identify Barriers to Hand Hygiene*. IDWeek. Sand Diego, CA. October 2015.
22. **Limper HM**, Carino S, Garcia-Houchins S, Slawsky L, Landon E. *Validation of an aggregate electronic monitoring system for Hand Hygiene*. IDWeek. Sand Diego, CA. October 2015.
23. Chugh A, Clardy C, Fromme BH, Kolek J, Koontz G, **Limper HM**, Ott J, Suett P, Bartlett AH. *A Daily Huddle: Improving Care Coordination in the Discharge Process.* University of Chicago Medicine's Quality & Safety Symposium. May 2016.
24. Pacholek G, Slawsky L, Albert D, Weber SG, **Limper HM**, Garcia-Houchins S, McHugh M, Wong L, Landon E. *The Big Wash: 100% Performance Is Attainable.* University of Chicago Medicine's Quality & Safety Symposium. May 2016.

Presentations at Scientific Meetings:

1. *Risk for HIV acquisition in the Chicago African-American Community: How risk pertains to social justice.* 2012. Chicago Freedom School's Annual Conference. Chicago, Illinois. Invited speaker.
2. *School-based Immunization: Applied Epidemiology.* Roundtable Discussion Speaker, American College of Epidemiology Annual Meeting. 2012. Chicago, Illinois. Peer-reviewed.
3. *Current Infectious Disease Practice: Policy, Protocols, and Pearls for the School.* Illinois Association of School Nurses Annual Conference. 2012. Lisle, Illinois. Invited speaker.
4. *Cervical Health and Human papilloma virus.* Love and Live: Breast and Cervical Cancer Center for Community Health and Vitality. 2012. Chicago, Illinois. Nominated speaker.
5. *Graduate Student Lessons Learned.* New Student Preview Day: Epidemiology and Biostatistics, University of Illinois at Chicago. 2013. Chicago, Illinois. Invited panelist speaker.
6. *HPV in the United States: Where are we now?* Women in Government, Fourth Annual Healthcare Summit. 2013. Washington, D.C. Nominated speaker.
7. *Societal Roles, Societal Structure, and Social Construction's Impact on Health.* Grand Valley State University, Social and Behavioral Health Graduate Course. 2015. Grand Rapids, Michigan. Invited guest lecturer.

Additional Training:

Preparing an Investigational New Drug Application	2010
Designing and Editing Tables and Graphs, University of Chicago	2011
CITI Training, Human Research Training for Investigators	2011, 2014
Fundamentals of Clinical Research, University of Chicago	2011
Immunization Educator Training, Chicago Area Immunization Campaign	2012
Creating Pivot Tables in Excel, University of Chicago	2013
Institute for Healthcare Improvement, IHI Open School Basic Level	2013