Continuous and Automated Measuring of Compliance of Hand-Hygiene Procedures Using Finite State Machines and RFID

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Health care associated infections (HAIs) affect up to one in twenty hospitalizations or 1.7 million persons annually in the U.S., exceeding four billion dollars in costs [1] and resulting in approximately 100,000 deaths. In Europe, there are an estimated five million annual cases of general nosocomial infections, infections acquired in a hospital, with 2.7% of cases (135,000 annually) being a contributor to death [2]. Although many factors contribute to the development of HAIs, hand hygiene is considered the single most important measure for limiting nosocomial transmission of pathogens [3]. Hand hygiene compliance is generally considered to be suboptimal and remains a constant challenge for infection control programs. Health regulatory and advisory agencies, such as the World Health Organization (WHO), the Centers for Disease Control and Prevention (CDC), and The Joint Commission, all recommend or demand that hospitals monitor hand hygiene compliance.

Basic research assessing the effect of compliance on the spread of diseases has relied on infrequent human observations that often provide insufficient data. In addition, despite the routine issuing of guidelines on proper hand hygiene practices by the WHO and the CDC, compliance rates among healthcare staff remains low with rates in 2000 ranging anywhere from 10% to 60%. Studies have found that when healthcare workers are reminded of the importance of following proper hygiene and of their own compliance performance, they are more likely to have an overall higher adherence rate. A low-cost system for automated and continuous measuring of compliance which is scalable to work in large healthcare facilities would be extremely beneficial for supporting basic research on the effect of hand hygiene compliance on pathogen transfer and for improving compliance by enforcing accountability of staff members.

In this paper, we present a novel method and prototype system developed for measuring hand-hygiene compliance in hospitals. The system was developed in a joint one-year project between Rochester Institute of Technology (RIT) and Rochester General Health System (RGHS) in the framework of the RIT-RGHS Alliance [4]. It makes use of low-cost radio frequency identification (RFID) technology [5] coupled with data processing using a finite state machine (FSM). The system was tested and validated in a patient room at Rochester General Hospital (RGH), and a pilot study measured compliance of staff members on the floor. The method proved to be reliable and provided interesting insights on the probability and trends of compliance. This proposed system promises to be very cost effective, scalable and virtually invisible to the staff members.

Introduction

Since human observation for compliance is prone to bias, many hospitals are looking towards automated solutions. There are sink-like devices where the hands of the worker are inserted into two holes in the unit and a mixture of water and an antimicrobial detergent is sprayed onto the hands. Other solutions include ZigBee (IEEE 802.15.4) powered ID badge holders to be worn by hospital staff, a chemical sensing device to be placed near gel dispensers, ZigBee bed monitors and software to log and report collected information.

There are concerns with the scalability of such systems to large-scale deployment in hospitals. When staff members use the hand gel, they must place their hands underneath the chemical sensor to be registered as having complied with the procedure. This system is good for food service environments but doesn't integrate well with hospital staff workflows where hand-hygiene is required upon entry into every room.

ZigBee (IEEE 802.15.4) powered ID badges worn by the staff members are battery powered and emit electromagnetic radiation when communicating. This means that the devices may interfere with existing communicating devices and will require periodic recharging.

RFID technology has undergone explosive growth, moving from relative obscurity to widespread adoption in the past two decades [5]. Currently, RFID systems are virtually everywhere, including automatic toll collection, shipment tracking, retail theft protection, inventory monitoring, payment systems, and passport identification. RFID tags can

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be detected even when there is no line of sight between the reader and the tag. Tags are able to contain significant amounts of information and include a microprocessor and memory, and RFID readers can detect many tags simultaneously. Tags are either active tags, semi-active tags, or passive tags. Passive RFID tags are by far the most widely used tag type, primarily because they are low in cost, require no recharging, and they do not emit wireless interference. A passive RFID tag works by receiving a signal that queries it and powers the response.

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The typical application for RFID in a healthcare environment is inventory monitoring. But other applications are for security for the hospital and for patients: to secure access to the hospital by authorized staff; to keep track of newborns to help prevent 'newborn theft'; and some hospitals have begun tagging all patients to allow both tracking and diagnostic security.

System Description

Our proposed system uses passive RFID tags attached to staff members' hospital ID badges with RFID readers placed in the patient rooms. It consists of multiple RFID-enabled alcoholic gel dispensers, staff identification cards with embedded passive RFID tags, a tag reader, and a web server. A single RFID-enabled dispenser is placed at the entrance to each patient's room and is connected to an additional antenna in the room. Every staff RFID tag contains a unique identification number, and each is detected separately by the reader. Each dispenser notifies the server when a staff RFID registers a gel activation event. The web server runs an application dedicated to collecting data from the readers and storing it in a database. The server's web front-end views real-time events and displays database entries in a requested timeframe.

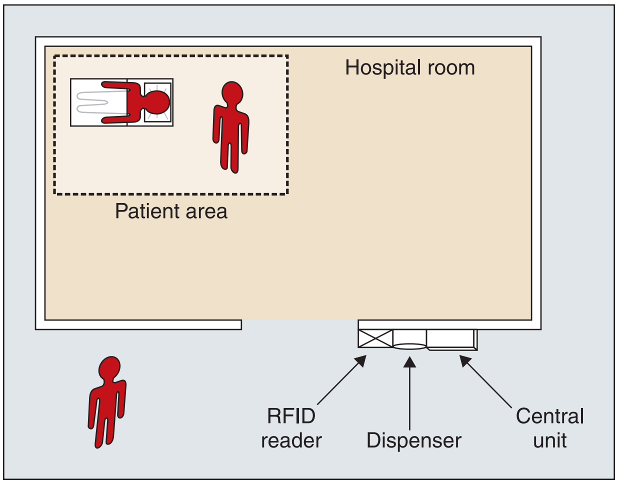

Fig. 1. Possible layout of a hospital patient's room including an RFID reader, dispenser and central unit.

Events are defined based on data obtained from the reader antennas and activation of the dispenser. The hand-sanitizing procedure is translated to an FSM, and events flow through the FSM representing the hand-hygiene protocol, which determines compliance or non-compliance. The system facilitates continuous and automatic measuring of staff compliance with hand-hygiene procedures. Fig. 1 shows a possible hospital patient's room and a location for the RFID reader, dispenser and central unit.

The benefits of the FSM design are to efficiently track human activity and provide low-cost deployment when scaled to a large facility. Many hospitals have an existing RFID infrastructure for security access and/or asset monitoring that could easily be expanded to compliance monitoring.

The FSM

An FSM is a model that operates on a logical sequence of events that represents the states: a staff member entered the room; the staff member did use or did not use the system's sanitizing gel; the staff member approached the patient or the staff member moved out of the room. Transitions between these states are caused by movement within the room which is detected by one or more RFID reader antennas. State transitions cause an input event, and an output event is emitted. When there is no activity, a timeout occurs. The idle, or default state, is called 'outside', corresponding to being outside of the patient's room and not being detected by the RFID readers. Since FSMs are deterministic, they are designed to determine compliance.

If one watches staff members for hand hygiene compliance, the task is relatively simple though mundane and prone to human bias. Determining compliance accurately using automated means is not trivial. Since there are certain events which need to occur in a certain sequence and since those events are detectable, the events which are logged by an RFID reader can be pushed through an event-driven FSM.

Measuring Compliance

Data from each employee's tag are run through the FSM. Every event logged for a tag (detection by one of the antennas or activation of the hand-gel dispenser) causes the tag to move through the FSM. The resulting 'walk' of a tag through the FSM produces a record of the history of states entered by the tag along with the time they occurred. Ultimately, the goal is to count the occurrences of compliance and non-compliance events. For our purposes, we are not interested in the absolute count of compliance and non-compliance events but do wish to find the trends in compliance over time; i.e., what is the average probability of compliance of individual staff members with respect to all patients, and what is the average probability of compliance of all staff members approaching an individual patient?

We define the measurable compliance $R_c(t)$ as a function of time:

$$R_c(t) = \frac{N_c(t)}{N_c(t) + N_{nc}(t)}, \quad (1)$$

where $N_c(t)$ is the number of compliance events during time span $[0,t]$ and $N_{nc}(t)$ is the number of non-compliance events during same time span. $R_c(t)$ is evaluated over a specific period of time, e.g., a day or night shift, or over asymptotically infinite time for estimating the average probability of compliance.

A Pilot Study at RGH

The prototype system consists of an Alien ALR-9650 RFID reader with a secondary external antenna attached and Alien ALN-9529 "Squiggle-SQ" RFID tags. The hand gel dispenser is fitted with an electronic switch and connected to a digital input port on the reader. The reader records the tag IDs with a timestamp and monitors the digital input connected to the hand gel dispenser to record when the dispenser is used. These events are then processed to determine compliance.

The FSM Design

At RGH, the hand-hygiene policy is that staff members must wash their hands using a sanitizing gel prior to approaching patients in their rooms. Fig. 2 shows the pilot study configuration of the room on floor 4800 at RGH. The entrance to the room is a small alcove. The gel dispenser is located on the left-hand side upon entrance. Staff members are allowed to be in the alcove without hand-hygiene to observe or communicate with patients from a sufficient distance where compliance is not needed. Once the staff member moves beyond the alcove and into the primary patient room area, compliance is required.

Fig. 3 shows the FSM developed for the room configuration at RGH. This FSM is centered on being "outside". From the "outside" state, the staff member can move to the "safety zone" state by being detected by the dispenser antenna, or possibly directly to the "patient zone" state by being detected by the patient antenna. From the "safety zone" state, the staff member can move to the "patient zone" state by being detected by the patient antenna, to the "pending comply" state by using the dispenser, or back "outside" by not being detected for a period of time. Once the staff member has used the dispenser and is waiting in the "pending comply" state, he/she just needs to enter the patient area and be detected by the patient antenna to move to the "complied" state. While in the "patient zone" state (implying the staff member did not wash hands yet), the staff member has a limited amount of time to reenter the safety zone before moving to the "didn't comply" state.

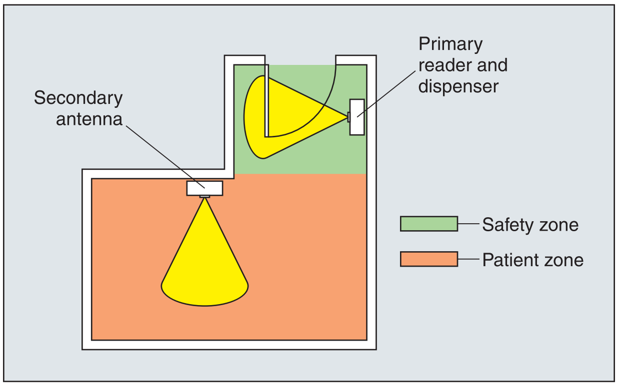

Fig. 2. Layout of a pilot room at Rochester General Hospital, NY, USA.

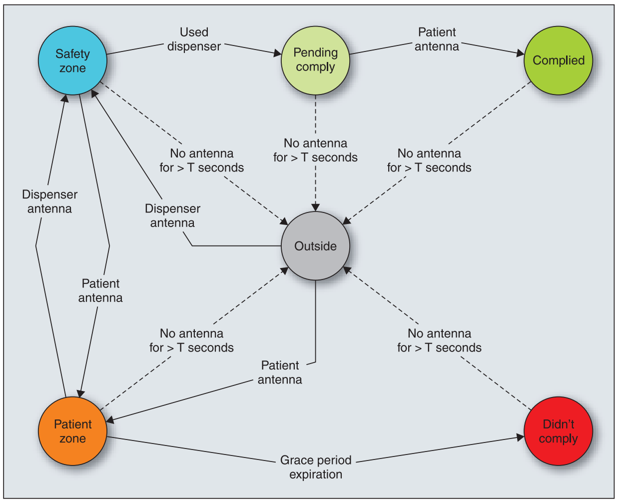

Fig. 3. Finite state machine developed for the pilot.

System Validation

The system was set up in a patient's room, and the placement of the RFID readers, the FSM, and locating blind spots in the room were validated by running test scripts. There were three test scripts, and two different people each ran the full suite. The first test was deemed the 'room peek' test, where compliance was not required. This consisted of ten repetitions of a person moving to some part of the 'safety zone'. The second test was non-compliance and was made of twelve repetitions of a person moving to specific locations in the room without using the dispenser first. The third test was for compliance and was twelve repetitions of using the dispenser before entering the patient zone.

The system performed well for all tested scripts. In addition, its performance was validated with parallel human observation during typical conditions. To allow observation, a secure remote internet connection was established to the server and to a webcam positioned in the room entrance. The image was blurred to protect privacy, and observations exceeding ten hours were conducted. The testing of the system under typical conditions allowed for a better setting of the timeout events in the FSM by fifteen to thirty seconds.

Gathering Data

ID badges were distributed to all staff members working on the floor and attending patients in the room with the RFID system. Each badge contained a pair of RFID tags (one on the front and one on the back). Data were collected over four

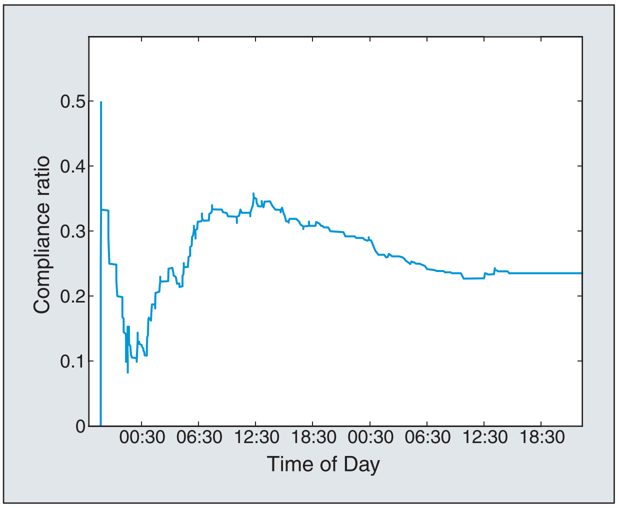

Fig. 4. Compliance ratio for a representative staff member.

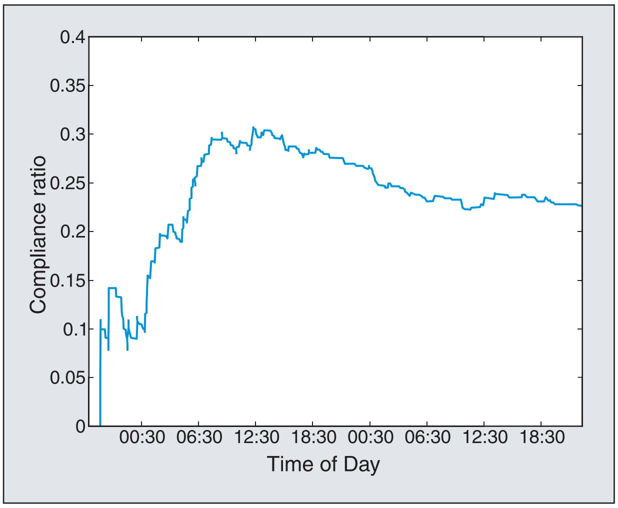

Fig. 5. Compliance ratio in the pilot room including all tags.

days and analyzed. Of the ID badges distributed to the staff, there were nine detected by the reader, though only five were deemed to contain representative data. The remaining four were detected by the safety-zone antenna only; the staff members were in the area but never actually entered the patient area. Of the five badges containing patient area activity, three of the tags spanned one 9-hour daytime shift (Monday, 8 a.m. to 5 p.m.), one of the other tags spanned 41 weekend hours (Friday afternoon until Sunday morning), and the last spanned 53 hours (Friday afternoon until Sunday evening). The staff members were asked to share ID tags, so the long records are not the activity of a single person.

Results

Fig. 4 depicts the compliance ratio as a function of time, $R_c(t)$ for a representative staff member. The x-axis is labeled in hours. It is clear that as time increases, the ratio converges to a value of 0.235. This value is an estimate of the probability that the staff member would comply with the hand-sanitizing procedure when approaching a patient.

Fig. 5 shows the compliance ratio for all tags combined over a 48-hour period. This presentation allows for measuring room (patient) specific compliance regardless of the staff member entering the room. When the compliance ratio measurement starts, $R_c(t)$ fluctuates significantly due to changes in the behavior of staff members over the course of a single day. Then, $R_c(t)$ reaches a value just over 0.2 which represents the average compliance ratio in the room. This means that only 20% of the time when staff members approached the patient, they complied with the hand-hygiene procedure.

Fig. 6 uses the same combined data set of all tags as the previous illustration, except the compliance ratio is passed through a sliding window of 8 hours. From this, the hourly compliance ratio clearly indicates a trend of higher compliance during the night. This implies that the presence of many co-workers and supervisors does not increase compliance, but rather that the low activity during night allows staff members to comply with procedures.

Summary

Nosocomial infections are a serious problem for healthcare environments with high costs in morbidity and malpractice lawsuits. It is widely accepted that the most effective method for reducing nosocomial infections is through hand-hygiene by hospital staff. Despite its importance, there are limited data on the compliance rates of staff members using hand-hygiene procedures, and available data demonstrate that compliance rates are extremely low. In this paper, we presented a method and accompanying prototype system for automated and continuous measurement of compliance with hand-hygiene procedures in hospitals. The method is based on the use of low-cost RFID technology coupled with FSMs to capture and measure compliance. Analysis resulted in tools for estimating the average probability of compliance and understanding the trends of compliance over time. In addition, real data from a pilot study in a hospital room demonstrated the ability to capture and measure compliance. This measurement

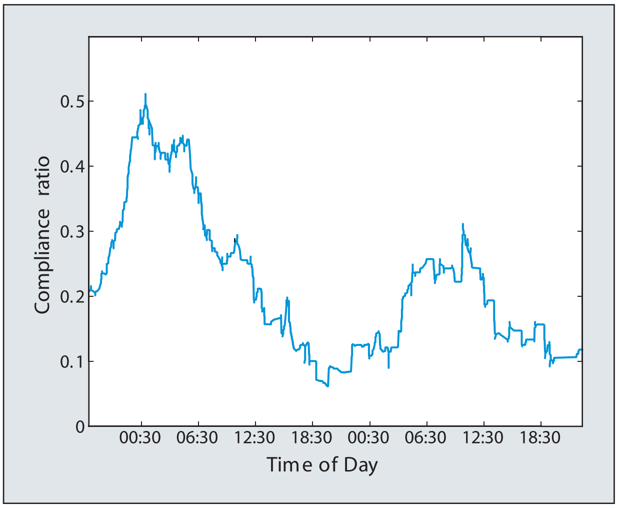

Fig. 6. Compliance in the pilot room using an observation sliding window of eight hours.

system allows basic research on the effect of compliance on infection rates, and it can help increase compliance through staff accountability.

Acknowledgement

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References

[1] M. Eber, R. Laxminarayan, E. Perencevich, and A. Malani, "Clinical and economic outcomes attributable to health care-associated sepsis and pneumonia," *Arch. Intern. Med.*, vol. 170, no. 4, pp. 347-353, 2010.

[2] D. Pittet, "Compliance with hand disinfection and its impact on hospital-acquired infections," *J. Hospital Infection*, vol. 48, pp. 40–46, 2001.

[3] D. Pittet, "Improving adherence to hand hygiene practice: a multidisciplinary approach," *Emerging Infectious Diseases*, vol. 7, no. 2, p. 234, 2001.

[4] The RIT&RGHS Alliance. [Online] Available: http://www.rit.edu/affiliate/rghs/.

[5] K. Finkenzeller, *RFID handbook: Fundamentals and applications in contactless smart cards and identification*, 2nd ed. Hoboken, NJ: John Wiley & Sons, 2003.

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For additional information and technical details, see these papers in our sister publication, the *IEEE Transactions on Instrumentation and Measurement:*

J. Bing, K. P. Fishkin, S. Roy, and M. Philipose, "Unobstrusive long-range detection of passive RFID tag motion," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 1, Feb. 2006.

A. F. C. Errington, B. L. F. Daku, and A. F. Prugger, "Initial position estimation using RFID tags: A least-squares approach:", *IEEE Trans. Instrum. Meas.*, vol. 59, no. 11, Nov. 2010.