


Original Article

Impact of an automated hand hygiene monitoring system and additional promotional activities on hand hygiene performance rates and healthcare-associated infections

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Abstract

Objective: Determine the impact of an automated hand hygiene monitoring system (AHHMS) plus complementary strategies on hand hygiene performance rates and healthcare-associated infections (HAIs).

Design: Retrospective, nonrandomized, observational, quasi-experimental study. Setting: Single, 93-bed nonprofit hospital.

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Methods: Hand hygiene compliance rates were estimated using direct observations. An AHHMS, installed on 4 nursing units in a sequential manner, determined hand hygiene performance rates, expressed as the number of hand hygiene events performed upon entering and exiting patient rooms divided by the number of room entries and exits. Additional strategies implemented to improve hand hygiene included goal setting, hospital leadership support, feeding AHHMS data back to healthcare personnel, and use of Toyota Kata performance improvement methods. HAIs were defined using National Healthcare Safety Network criteria.

Results: Hand hygiene compliance rates generated by direct observation were substantially higher than performance rates generated by the AHHMS. Installation of the AHHMS without supplementary activities did not yield sustained improvement in hand hygiene performance rates. Implementing several supplementary strategies resulted in a statistically significant 85% increase in hand hygiene performance rates ($P < .0001$). The incidence density of non-*Clostridioies difficile* HAIs decreased by 56% ($P = .0841$), while *C. difficile* infections increased by 60% ($P = .0533$) driven by 2 of the 4 study units.

Conclusion: Implementation of an AHHMS, when combined with several supplementary strategies as part of a multimodal program, resulted in significantly improved hand hygiene performance rates. Reductions in non-*C. difficile* HAIs occurred but were not statistically significant.

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Monitoring hand hygiene (HH) compliance of healthcare personnel (HCP) and providing them with feedback is an essential element of multimodal strategies to improve HH.¹ Direct observation of HCP by trained observers is currently the gold standard for estimating HH compliance rates.^{2–4} Although direct observation has several unique advantages, its limitations have generated interest in supplemental methods for monitoring HH performance.^{3,5–8} To address this issue, automated HH monitoring systems (AHHMSs) have been developed, the advantages and limitations of which have been identified.^{3,9–12} Several studies have found that AHHMS installation without sufficient supplementary activities may not result in improved HH performance rates.^{9,13,14} Adoption of the AHHMS by hospitals is hampered by a paucity of published evidence regarding their ability to yield sustained HH performance

rate improvements and to reduce healthcare-associated infections (HAIs).³

For years, Hanover Hospital, a 93-bed nonprofit acute-care facility with 6 nursing units, often reported HH compliance rates of 80%–95%, based on direct observations. However, informal observations by the hospital's quality improvement department questioned the accuracy of these reported rates. In response, in 2014 the hospital formed a "Do No Harm" team designed to reduce patient harm. In addition, the hospital selected a group monitoring system (Smartlink activity monitoring system, GOJO Industries, Akron, OH) with a high degree of sensitivity and positive predictive value.¹⁵ In this article, we describe the impact of combining an AHHMS with multiple promotional activities on HH performance and HAIs.

Methods

HH compliance rates generated by routine direct observations

The hospital has recorded HH compliance direct observation results in a dedicated database since 2009. In each hospital unit,

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1 or 2 individuals are trained and are required to covertly observe ≥ 10 HH opportunities per quarter on their unit.

Automated HH monitoring system

Elements of the Smartlink AHHMS have been described in detail.¹⁵ Alcohol-based hand rub (ABHR) and soap dispensers record each dispersal as an HH event (HHE). Activity monitors near each patient room doorway detect each entry into and exit from the room as an HH opportunity (HHO). Data captured by dispensers and activity monitors are sent to a secure cloud-based server that stores the information at the device level. Unit HH performance rates (estimates of compliance) are calculated by dividing HHEs by HHOs. Near real-time performance rates can be viewed on a computer display in each nursing unit. Performance rates are distributed to “Do No Harm” team members and unit leaders on a weekly basis.

In June 2014, the AHHMS was installed on 1 medical–surgical nursing unit (unit A) to better understand HH performance rates and increase awareness of the importance of HH. The AHHMS was subsequently installed in a stepwise manner in another medical-surgical unit (unit B) in August 2015, in a progressive care/step-down unit (unit C) in December 2016, and in a mixed medical-surgical intensive care unit (unit D) in April 2017. The AHHMS was not installed on the pediatrics or maternity units, which rarely report HAIs.

Goal setting

Following AHHMS installation, nursing unit team members set goals for improved HH performance rates.^{16,17} As goals were met, units celebrated their achievements and set new goals.

Frontline ownership initiative (Intervention I)

The hospital consulted an expert on using frontline ownership (FLO) to promote improved compliance with HH recommendations.¹⁸ The expert visited Hanover Hospital on 3 occasions between August 2015 and June 2016 to assist the hospital in implementing FLO.

Support by hospital leadership (Intervention II)

In 2014 and 2015, hospital leadership supported AHHMS installation on units A and B. In mid-September 2016, hospital leadership sent 6 frontline nursing staff, the infection preventionist, and the vice president for medical affairs to visit a large hospital in Chicago that had achieved sustained increases in HH compliance rates using the same AHHMS as part of a multimodal strategy.^{15,19} Meetings with the physician leading the Chicago hospital’s HH campaign included discussions of methods for analyzing AHHMS data and additional promotional activities. Following the visit, administrators approved stepwise installation of the AHHMS on units C and D.

Do No Harm team HH audit

In September 2016, members of the Do No Harm team, which included HCP from every unit and all ancillary departments, performed covert direct observations of HH compliance upon room entry and exit on all nursing units.

Toyota Kata methodology (Intervention III)

In February 2017, the hospital began to adopt the Toyota Kata performance improvement methodology.^{20,21} A Kata involves changing behavior using a step-by-step process with experimentation by frontline personnel and using a “Plan, Do, Check, Act” (PDCA) cycle to achieve the desired behavior. The hospital provided mandatory training for management and leadership staff and developed an institutional commitment to the philosophy. Unit A started its HH Kata project in February 2017, and unit B chose HH improvement as their first Kata project in late March 2017. On each unit, 1 person each day was assigned to wear an “HH Sheriff” badge and reminded personnel to perform HH. Efforts were made to improve HH when passing meal trays. HH rates were reported at each shift huddle and at a daily “safety huddle,” data were posted in staff lounges and reported to senior leadership. HCP were coached when compliance decreased.

HAI prevention and surveillance

Bundles for prevention of central-line-associated bloodstream infections (CLABSIs) and of catheter-associated urinary tract infections (CAUTIs) were in place prior to implementation of the AHHMS. Surveillance for HAIs was performed by the hospital’s infection control program using National Healthcare Safety Network (NHSN) definitions.²²

Monthly HAI data reported to the Pennsylvania Department of Health through June 2018 were available for the following HAIs: methicillin-resistant *Staphylococcus aureus* (MRSA) and vancomycin-resistant *Enterococcus* (VRE) bloodstream infections, CLABSIs, CAUTIs, and *Clostridioides difficile* infections (CDIs). Because the number of HAIs per month was low on all 4 units, incidence density data for the 4 units, expressed as the number of HAIs per 10,000 patient days, were aggregated for the purposes of data analysis. Furthermore, because increased HH (and use of alcohol-based hand rub) may not have the same impact on CDI as on other infections,^{23,24} HAIs were divided into 2 groups: CDI and all other reported HAIs combined (non-CDI).

Statistical analyses

We fit 2 types of mixed-effects Poisson autoregressive (AR) time-series models to the HH and HAI data separately. First, a general additive model²⁵ (ie, a smoother via penalized regression splines) was fit to assess nonlinear trends. Second, to compare rates among the 4 periods, a linear model was fit with a random effect for unit, a covariate for month, a fixed effect to account for the baseline, and 3 intervention periods: (1) baseline period up to August 2015, (2) period after FLO (Intervention I), September 2015–September 2016, (3) period after Chicago visit (Intervention II), October 2016–March 2017, (4) period after Toyota Kata Education (Intervention III), April 2017–June 2018, and the month-by-intervention period interaction.²⁶ Both types of models weighted the number of HH or HAI events by the number of opportunities or the number of patient days, respectively. Seasonal effects were modeled by smoothing terms. Units A and B had the most experience with the AHHMS, so units A and B were analyzed separately. Model fit was assessed graphically by scatter, autocorrelation, and partial autocorrelation plots of the model’s residuals. Model fit was also assessed using augmented Dickey-Fuller (ADF) unit root tests.²⁷ A separate mixed-effects Poisson model was used to investigate the relationship between HAI rates (both CDI and non-CDI) and HH performance rates. The lagged relationship between HH

Table 1. Average and Ranges of Hand Hygiene (HH) Compliance Rates Generated by Routine Direct Observational Surveys Before and After Installation of the AHHMS, by Nursing Unit

Unit	Range of Quarterly Compliance Rates (# HHEs/# HHOs) Before AHHMS	Average Quarterly Compliance Rate Before AHHMS, %	Range of Quarterly Compliance Rates (No. of HHEs/No. of HHOs) After AHHMS Installation	Average Quarterly Compliance Rate After AHHMS Installation, %
A	57.1% (8/14) to 73.3% (11/15)	65.5	47.8% (11/23) to 100% (1/1)	79.6
B	0% (0/1) to 96.25 (25/26)	88.3	65.2% (15/23) to 100% (2/2)	84.7
C	45.5% (5/11) to 100% (93/93)	94.3	72.2% (13/18) to 100% (1/1)	76.7
D	71.4% (10/14) to 99.1% (107/108)	94.8	90% (9/10)	90

Note. AHHMS, automated hand hygiene monitoring system; HHE, HH events; HHO, HH opportunities.

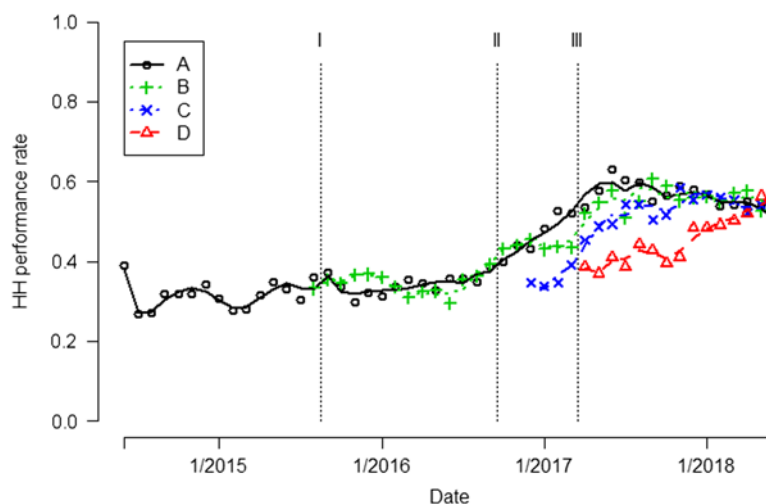


Fig. 1. Hand hygiene (HH) performance rates are indicated by different colored symbols for each unit. Trend of the HH performance rates are indicated by different colored curves. The vertical dashed lines indicate when 3 interventions occurred. Note. Intervention I, frontline ownership initiative (FLO); Intervention II, Chicago visit; Intervention III, Toyota Kata method.

performance and HAI rates was assessed at units A and B using a vector autoregression model (VAR) to HH and HAI data simultaneously and then tested for Granger causality.²⁸ All statistical calculations were performed using R version 3.4.1 software.²⁹ R packages *MASS*³⁰ and *nlme*³¹ were used to fit the AR models; *vars* was used to fit the VAR models and was used to perform a Granger test,²⁸ and *tseries* was used to perform ADF tests.³² Individual Wald 2-sided *P* values and 95% 2-sided CIs are reported throughout. To maintain a 95% family-wise false discovery rate over the test results (Tables 2 and 3), the Benjamini-Hochberg method requires that the individual *P* values in the tables be compared against .015 to determine statistical significance.

Results

Hand hygiene compliance rates by routine direct observations

Hand hygiene compliance rates generated by direct observations since January 2014 were analyzed. Average (and range) compliance rates before and after installation of the AHHMS on each unit are shown in Table 1. The average quarterly compliance rates on all 4 units ranged from 65.5% to 94.8%.

HH performance rates determined by the AHHMS

Unit A. During the first month after AHHMS installation on unit A in June 2014, the AHHMS HH performance rate was initially

38.9%, but it rapidly fell to a baseline rate of 26.7% by the next month. HH performance rates varied from 26.7% to 38.9% in the period June 2014–August 2015 (Fig. 1). Following implementation of the FLO concept, AHHMS-based performance rates gradually increased to 38.5% in September 2016 (Fig. 1).

In September 2016, covert direct observations by Do No Harm team members determined a 38% (8 of 21) compliance rate on unit A, which was similar to the 38.5% AHHMS rate. The similarity of rates obtained by the AHHMS and direct observation improved HCP acceptance of performance rates generated by the AHHMS.

Following implementation of the Toyota Kata methodology and the use of the PDCA tool, performance rates on unit A continued to increase from 38.5% to a maximum of 62.9% in June 2017, with some decline in early 2018 (Fig. 1). After all 3 interventions, there was an aggregate 81% (95% CI, 70%–92%) increase in rates over the baseline ($P < .0001$) (Table 2).

Unit B. During the first month after installation of the AHHMS on unit B in August 2015, the HH performance rate was 33.1%. In the period September 2015–September 2016 after the first intervention, rates generated by the AHHMS varied from 29.5% to 39.2% (Fig. 1). In unit B, an aggregate 61% (95% CI, 60%–62%) increase in HH rates occurred during the last 2 intervention periods (October 2016–June 2018) over the initial intervention (September 2015–September 2016; $P < .0001$) (Table 2).

Unit C. In the month after installation of the AHHMS on unit C in December 2016, the HH performance rate was 34.7%.

Table 2. Hand Hygiene (HH) Performance Rates Pooled Over all 4 Units (A–D) and Separately at Units A and B for Which Data Were Collected During all 3 Intervention Periods^a

Unit(s)	Intervention Period	Months	No. of HHOs	HH Rate, %	% Change From 1 st Period, %	95% CI of % Change	P Value
A–D	None	To 8/2015	2,584,782	28	...	...	...
	After FLO	9/2015–9/2016	3,415,818	32.2	15	4.4–26	.0063
	After Chicago	10/2016–3/2017	1,855,913	40.6	45	31–61	<.0001
	After Toyota	4/2017–6/2018	6,145,036	51.8	85	68–103	<.0001
A	None	To 8/2015	2,499,722	31	...	...	...
	After FLO	9/2015–9/2016	2,190,347	34	10	2.9–17	.0113
	After Chicago	10/2016–3/2017	904,047	47.1	52	41–64	<.0001
	After Toyota	4/2017–6/2018	1,955,735	56.1	81	70–92	<.0001
B	After FLO	9/2015–9/2016	1,225,471	35	...	...	...
	After Chicago	10/2016–3/2017	546,228	44.5	27	26–28	<.0001
	After Toyota	4/2017–6/2018	1,300,753	56.4	61	60–62	<.0001

Note. HHOs, hand hygiene opportunities; CI, confidence interval; FLO, frontline ownership.

^aTwo-sided *P* values are reported for the test that HH rates increased compared to the first period (baseline for A–D and A; initial intervention period for B).

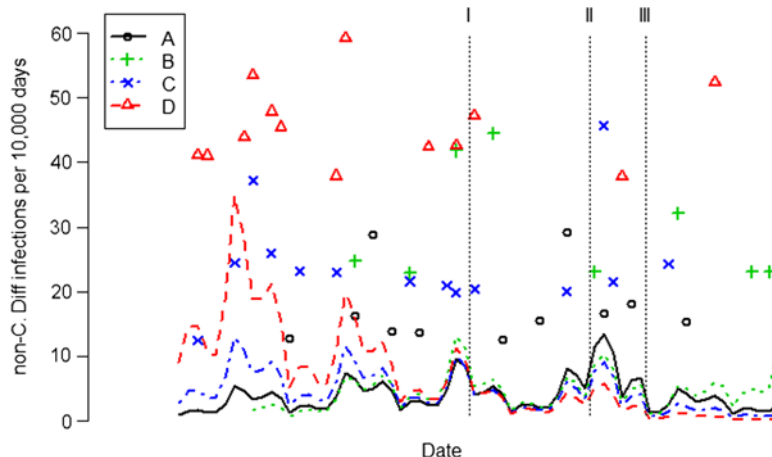


Fig. 2. Monthly non-CDI (MRSA, VRE, ESBL, CLABSI and CAUTI) for each unit are indicated by different colored symbols. Most months no non-CDI were reported (if plotted, they would form a solid horizontal line at 0), so only nonzero rates are shown. Trend of the non-CDI rates are indicated by different colored curves. Note. CDI, *Clostridioides difficile* infection; MRSA, methicillin-resistant *Staphylococcus aureus*; VRE, vancomycin-resistant *Enterococcus*; ESBL, extended-spectrum β -lactamase; CLABSI, central-line-associated bloodstream infection; CAUTI, catheter-associated urinary tract infection. Intervention I, frontline ownership initiative (FLO); Intervention II, Chicago visit; Intervention III, Toyota Kata method.

Performance rates in the first quarter of 2017 averaged 35.9%, and they increased progressively to a maximum of 58.5% in November 2017. They then remained above 52% for the rest of the study (Fig. 1).

Unit D. In the month after the AHHMS was installed on unit D in April 2017, the HH performance rate was 38%. Subsequently, performance rates increased each quarter, reaching a maximum of 56.3% in May 2018 (Fig. 1).

Pooled over all 4 units, the aggregate HH performance rate for the period June 2014–August 2015 was 28% (95% CI, 25%–32%). Table 2 shows steady, statistically significant increases in the HH performance rate after each of the 3 interventions were enacted, resulting in an 85% (95% CI, 68%–103%) increase from the baseline after the implementation of all 3 interventions ($P < .0001$).

HAI rates

Pooled over all 4 units, non-CDI rates were at 5.7 per 10,000 patient days and showed a flat trend in the 14-month baseline

period before FLO intervention (June 2013–August 2015, 95% CI, –3.0% to 5.0% per month; $P = 0.652$) (Fig. 2). That trend decreased by 8% (95% CI, –24% to 11%; $P = 0.3938$) in the 13 months after the FLO intervention, resulting in 3.7 non-CDI per 10,000 days (Table 3). Greater reductions occurred in 2017 and early 2018 after the addition of the Toyota Kata methodology, which resulted in a 2.5 per 10,000 non-CDI (from April 2017 through June 2018), a 56% decrease (95% CI, –82% to 10%; $P = .0841$). The incidence density rates of non-CDI on unit D, which were higher than the other 3 units, were already trending downward from 2013 to 2016 before the installation of the AHHMS in April 2017 and remained flat after AHHMS installation (Fig. 2).

The incidence density of CDI increased after AHHMS installation on units C and D and remained flat on Units A and B (Table 3 and Fig. 3). Pooled across the 4 units, the CDI rate was 7.9 per 10,000 patient days and exhibited a flat trend (95% CI, –4.0% to 2.3% per month) in the 14-month baseline period before the FLO intervention (from June 2013 through August 2015). After all

Table 3. Hospital-Acquired Infection Rates Pooled Over all 4 Units^a

Intervention Period	Months	Total Patient Days	CDI Rate	% Change from 1 st Period	95% CI of % Change	P Value	Non-CDI Rate	% Change from 1 st Period	95% CI of % Change	P Value
None	To 8/2015	56,882	7.9	...	...	...	5.7	...	...	...
After FLO	9/2015–9/2016	24,347	6.1	–23	–58 to 42	.4116	3.7	–35	–71 to 44	.2939
After Chicago	10/2016–3/2017	10,528	8.3	5	–53 to 136	.9015	7.2	26	–47 to 197	.6061
After Toyota	4/2017–6/2018	24,722	12.6	60	–0.1 to 155	.0533	2.5	–56	–82 to 10	.0841

Note. CDI, *C. difficile* infection; non-CDI, other HAIs; CI, confidence interval; FLO, frontline ownership.

^aTwo-sided *P* values are reported for the test that HAI rates differed from the baseline.

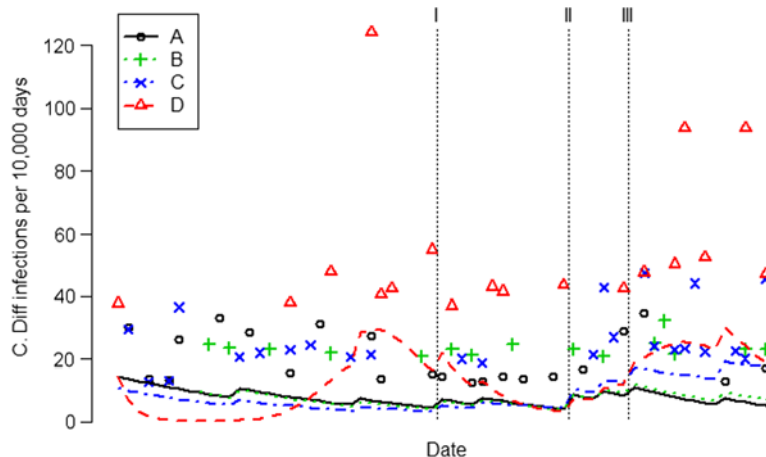


Fig. 3. Monthly CDI rates for each unit are indicated by different colored symbols. Most months no CDI were reported (if plotted, they would form a solid horizontal line at 0), so only nonzero CDI rates are shown. Trend of the CDI rates are indicated by different colored curves. Note. CDI, *Clostridioides difficile* infection. Intervention I, frontline ownership initiative (FLO); Intervention II, Chicago visit; Intervention III, Toyota Kata method.

3 interventions, the incidence of CDI rose 60% (95% CI, –0.1% to 155%; $P = .0533$). However, that increase was totally attributable to units C and D, which had less experience with the AHHMS. Units A and B exhibited a 63% (95% CI, –86% to 1.1%) decrease in CDI ($P = .0538$) after all 3 interventions compared to units C and D.

Pooled over all 4 units, we found no significant association between the increase in HH rate and a change in the same month of the CDI rate ($P = .9143$) or non-CDI rate ($P = .2374$). When looking only at units A and B over the period September 2015–June 2018 for which both units had data, the data failed to show time-delayed effects (up to 6 months) of HH performance rates on either CDI ($P = .1651$) or non-CDI rates ($P = .1159$).

Discussion

The Hanover Hospital experience with improving HH performance illustrates several important concepts related to promotion and monitoring of HH practices. For example, average HH compliance rates from direct observations (76.7%–90%) on the 4 units when the AHHMS was installed were consistently higher than those generated by the AHHMS, which most likely reflects overestimation of compliance rates due to the Hawthorne effect.^{6,9,13} Exaggerated compliance rates via direct observations may also be influenced by inadequate sample sizes.^{2,5} For example, following AHHMS installation on unit A, direct observational surveys measured 10–87 HHOs per quarter, compared to 468,452 HHOs per quarter on average recorded by the AHHMS.

Introducing the FLO concept was associated with intermittent improvement of 10% in performance rates on units A ($P = .0113$)

and B ($P < .0001$). In September 2016, the hospital paid for multiple nurses and an administrator to visit an out-of-state institution that had successfully implemented the same AHHMS, which demonstrated to HCP the commitment the hospital leadership had made to using the AHHMS. Insights gained during the visit resulted in new supplementary activities, including making signage and posters regarding HH and discussions on nursing units and with the Do No Harm team about ideas obtained during the trip. These activities had a substantial impact on HH performance rates on units A (52% increase over the baseline; $P < .0001$) and B (27% increase over FLO; $P < .0001$). Finally, the application of the Toyota Kata methodology to HH activities in early 2017 resulted in further substantial improvements of 85% (95% CI, 68%–103%; $P < .0001$) compared to the baseline in HH performance rates on units A–D (Table 2 and Fig. 1).

Although downward trends in non-CDI HAI rates occurred during the study period, the low baseline rate resulted in the study being underpowered to demonstrate a statistically significant reduction in HAI rates (Table 3). Other studies have also found an association between the use of an AHHMS and varying degrees of reduction of selected HAIs.^{33–35} Failure to achieve reductions in CDI may be related to confounding variables such as antimicrobial stewardship activities, compliance with glove use when caring for patients with CDI, handwashing practices, and/or surface disinfection protocols.^{36,37}

Limitations of the study include its quasi-experimental design with stepwise implementation of multiple interventions. Because there was no formal control group in which supplementary promotional activities were implemented in the absence of the AHHMS,

it is possible that HH performance improvements may have been achieved without AHHMS installation. However, between June 2014 and installation of the AHHMS on units C and D, direct observations revealed that compliance rates remained at high levels without substantial improvement, despite supplementary activities implemented by the hospital. Critical assessment of cost-effectiveness, short-term performance changes (eg, the unit A HH performance rate declined in early 2018), unit culture, and leaders would have been good additions to this study. Finally, the small hospital size may be the limit generalizability of our findings.

The lack of sustained improvement in HH performance rates observed on unit A during the first year after AHHMS installation (Fig. 1) illustrates that the implementation of an AHHMS may not lead to improved HH practices unless it is part of a multimodal strategy that includes supplementary promotional activities.^{9,13,14} Hanover Hospital personnel believe that the combination of feedback of quantitative assessments of HH performance provided by the AHHMS plus supplemental promotional activities is responsible for the significant improvements in HH practices. Hanover Hospital's experience is consistent with other studies reporting that complementary activities such as goal setting, reward incentives and accountability can result in improved HH practices when added to an AHHMS or basic multimodal strategies recommended by the World Health Organization.^{14,17,38}

In conclusion, providing HCP with quantitative HH performance data from an AHHMS in combination with multiple supplementary promotional activities resulted in a significant and sustained increase in HH performance rates. Reductions in HAIs occurred but were not statistically significant. Additional studies that include AHHMSs as part of a multimodal strategy are needed to better define the ability of AHHMSs to produce sustained improvements in patient safety by reducing HAIs.

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Conflicts of interest. J.M.B. and A.E.P. are consultants for GOJO Industries. P.W. and J.W.A. are employees of GOJO Industries.

References

1. WHO guidelines for hand hygiene in health care. World Health Organization website. www.who.int/gpsc/5may/tools/978924159706/en/. Published 2009. Accessed October 18, 2018.
2. Sax H, Allegranzi B, Chraït MN, *et al*. The World Health Organization hand hygiene observation method. *Am J Infect Control* 2009;37:827–834.
3. Ward MA, Schweizer ML, Polgreen PM, *et al*. Automated and electronically assisted hand hygiene monitoring systems: a systematic review. *Am J Infect Control* 2014;42:472–478.
4. Sax H, Boyce JM. Monitoring hand hygiene performance. In: Pittet D, Allegranzi B, Boyce JM (editors). *Hand Hygiene: A Handbook for Medical Professionals*. Chichester, UK: John Wiley & Sons; 2017:162–171.
5. Yin J, Schacht Reisinger H, Vander Weg M, *et al*. Establishing evidence-based criteria for directly observed hand hygiene compliance monitoring programs: a prospective, multicenter cohort study. *Infect Control Hosp Epidemiol* 2014;35:1163–1168.
6. Srigley JA, Furness CD, Baker GR, Gardam M. Quantification of the Hawthorne effect in hand hygiene compliance monitoring using an electronic monitoring system: a retrospective cohort study. *BMJ Qual Saf* 2014;23:974–980.
7. Boyce JM. Electronic monitoring in combination with direct observation as a means to significantly improve hand hygiene compliance. *Infect Control Hosp Epidemiol* 2017;45:528–535.
8. Masroor N, Doll M, Stevens M, Bearman G. Approaches to hand hygiene monitoring: from low to high technology approaches. *Int J Infect Dis* 2017;65:101–104.
9. Conway LJ, Riley L, Saiman L, *et al*. Implementation and impact of an automated group monitoring and feedback system to promote hand hygiene among health care personnel. *Jt Comm J Qual Patient Saf* 2014;40:408–417.
10. Pineles LL, Morgan DJ, Limper HM, *et al*. Accuracy of a radiofrequency identification (RFID) badge system to monitor hand hygiene behavior during routine clinical activities. *Am J Infect Control* 2014;42:144–147.
11. Ellingson K, Polgreen PM, Schneider A, *et al*. Healthcare personnel perceptions of hand hygiene monitoring technology. *Infect Control Hosp Epidemiol* 2011;32:1091–1096.
12. Boyce JM, Cooper T, Lunde A, Yin J, Arbogast J. Impact of an electronic hand hygiene monitoring system trial on hand hygiene compliance in a surgical intensive care unit and general medical ward. Abstract no. 1008. Presented at IDWeek 2012. October 19, 2012, San Diego, CA.
13. Kwok YL, Juergens CP, McLaws ML. Automated hand hygiene auditing with and without an intervention. *Am J Infect Control* 2016;44:1475–1480.
14. Edmonds-Wilson S, Pelz R, Moore L. Electronic hand hygiene monitoring with a complementary improvement program significantly increases hand hygiene rates. Presented at the 2016 Annual Meeting of the Association for Professionals in Infection Control and Epidemiology, June 2016, in Charlotte, NC.
15. Limper HM, Slawsky L, Garcia-Houchins S, *et al*. Assessment of an aggregate-level hand hygiene monitoring technology for measuring hand hygiene performance among healthcare personnel. *Infect Control Hosp Epidemiol* 2017;38:348–352.
16. Al-Tawfiq JA, Abed MS, Al-Yami N, Birrer RB. Promoting and sustaining a hospital-wide, multifaceted hand hygiene program resulted in significant reduction in health care-associated infections. *Am J Infect Control* 2013;41:482–486.
17. Luangasanatip N, Hongsuwan M, Limmathurotsakul D, *et al*. Comparative efficacy of interventions to promote hand hygiene in hospital: systematic review and network meta-analysis. *BMJ* 2015;351:h3728.
18. Zimmerman B, Reason P, Gitterman L, Christian J, Gardem M. Front-line ownership: generating a cure mindset for patient safety. *Healthcare Pap* 2013;13:6–23.
19. Landon E, Pacholek G, Runjo D, *et al*. Sustained improvement in hand hygiene compliance using a decentralized, technology-based approach. Abstract no. 1324. Presented at IDWeek 2017, October 6, 2017, San Diego, CA.
20. Ellingson K, Haas JP, Aiello AE, *et al*. Strategies to prevent healthcare-associated infections through hand hygiene. *Infect Control Hosp Epidemiol* 2014;35 Suppl 2:S155–S178.
21. Merguerian PA, Grady R, Waldhausen J, *et al*. Optimizing value utilizing Toyota Kata methodology in a multidisciplinary clinic. *J Pediatr Urol* 2015;11:228–236.
22. CDC/NHSN surveillance definitions for specific types of infections. Centers for Disease Control and Prevention website. https://www.cdc.gov/nhsn/pdfs/pscmanual/17/pscnsinfdef_current.pdf. Published 2017. Accessed October 18, 2018.
23. Vernaz N, Sax H, Pittet D, *et al*. Temporal effects of antibiotic use and hand rub consumption on the incidence of MRSA and *Clostridium difficile*. *J Antimicrob Chemother* 2008;62:601–607.
24. Kaier K, Hagist C, Frank U, Conrad A, Meyer E. Two time-series analyses of the impact of antibiotic consumption and alcohol-based hand disinfection on the incidences of nosocomial methicillin-resistant *Staphylococcus aureus* infection and *Clostridium difficile* infection. *Infect Control Hosp Epidemiol* 2009;30:346–353.
25. Wood SN. Stable and efficient multiple smoothing parameter estimation for generalized additive models. *J Am Stat Assoc* 2004;99:673–686.
26. Zuur AF, Ieno EN, Walker N, Saveliev AA, Smith GM. *Mixed Effects Models and Extensions in Ecology with R*. New York: Springer; 2009.

27. Shumway RH, Stoffer DS. *Time Series Analysis and Its Applications with R Examples*, 2nd edition. New York: Springer; 2006.
28. Pfaaf B. *Analysis of Integrated and Cointegrated Time Series with R*, 2nd edition. New York: Springer; 2008.
29. R Core Team. A language and environment for statistical computing. R Project website. <https://www.R-project.org/>. Published 2017. Accessed October 18, 2018.
30. Venables WN, Ripley BD. *Modern Applied Statistics with S*, 4th edition. New York: Springer; 2002.
31. Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team. *nlme: linear and nonlinear mixed effects models*. R package version 3.1-131. R Project website. <https://CRAN.R-project.org/package=nlme>. Published 2017. Accessed October 18, 2018.
32. Trapletti A, Hornik K. *tseries: Time series analysis and computational finance*. R package version 0.10-45. R Project website. <https://CRAN.R-project.org/package=tseries>. Published 2018. Accessed October 18, 2018.
33. Swoboda SM, Earsing K, Strauss K, Lane S, Lipsky BA. Electronic monitoring and voice prompts improve hand hygiene and decrease nosocomial infections in an intermediate care unit. *Crit Care Med* 2004;32:358–363.
34. Venkatesh AK, Lankford MG, Rooney DM, *et al*. Use of electronic alerts to enhance hand hygiene compliance and decrease transmission of vancomycin-resistant *Enterococcus* in a hematology unit. *Am J Infect Control* 2008;36:199–205.
35. McCalla S, Reilly M, Thomas R, McSpedon-Rai D, McMahon LA, Palumbo M. An automated hand hygiene compliance system is associated with decreased rates of healthcare-associated infections. *Am J Infect Control* 2017;45:492–497.
36. Dubberke ER, Carling P, Carrico R, *et al*. Strategies to prevent *Clostridium difficile* infections in acute care hospitals: 2014 update. *Infect Control Hosp Epidemiol* 2014;35:628–645.
37. Sitzlar B, Deshpande A, Fertelli D, *et al*. An environmental disinfection odyssey: evaluation of sequential interventions to improve disinfection of *Clostridium difficile* isolation rooms. *Infect Control Hosp Epidemiol* 2013;34:459–465.
38. Edmisten C, Hall C, Kernizan L, *et al*. Implementing an electronic hand hygiene monitoring system: lessons learned from community hospitals. *Am J Infect Control* 2017;45:860–865.