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Review

Hand hygiene monitoring technology: a systematic review of efficacy

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SUMMARY

Electronic and video monitoring systems (EMS/VMS) may improve hand hygiene by providing feedback, real-time reminders or via the Hawthorne effect. The aim of this systematic review was to assess the efficacy of EMS/VMS in improving hand hygiene or reducing the incidence of healthcare-associated infection (HCAI). Experimental and quasi-experimental studies were included if they measured any hand hygiene outcome and/or HCAI incidence. Of the studies included, seven used system-defined compliance (SDC) ($N = 6$) or hand hygiene event rate ($N = 1$) as their outcome. SDC differed for all systems. Most ($N = 6$) were single ward studies. Two uncontrolled pretest–post-test studies evaluating EMS that provided voice prompts showed increases in SDC, but risk of bias was high. Two uncontrolled time-series analyses of VMS that provided aggregate feedback demonstrated large, sustained improvement in SDC and were at moderate risk of bias. One non-randomized controlled trial of EMS with aggregate feedback found no difference in hand hygiene frequency but was at high risk of bias. Two studies evaluated EMS providing individual feedback and real-time reminders. A pretest–post-test study at high risk of bias showed an increase in SDC. An RCT at low risk of bias showed 6.8% higher SDC in the intervention arm partially due to a fall in SDC in the control arm. In conclusion, the overall study quality was poor. The study at lowest risk of bias showed only a small increase in SDC. VMS studies at moderate risk of bias showed rapid and sustained increases in SDC. Data were insufficient to recommend EMS/VMS. Future studies should prioritize testing of VMS using stronger study designs including control arms and validated, system-independent measures of hand hygiene.

Introduction

Hand hygiene monitoring technology (HHMT) is a potential solution to the problem of poor healthcare worker (HCW) hand hygiene compliance.[1–3] HHMT includes simple systems that count alcohol-based hand rub (ABHR) or soap dispensing events

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and complex systems that provide estimates of compliance and/or real-time hand hygiene reminders. HHMT may improve compliance through the provision of enhanced feedback, real-time reminders, or through an enhanced Hawthorne effect created by continuous monitoring.[4]

There are also issues with HHMT as it may be expensive and may not be acceptable to HCWs due to concerns about privacy, accuracy, or the need to wear additional devices or modify workflow.[1,2,5] HHMT uses different algorithms to define compliance or measures hand hygiene frequency instead of compliance, and it is not clear how these measures correlate with directly observed compliance. Before HHMT is adopted, its efficacy in improving hand hygiene and/or reducing the incidence of healthcare-associated infection (HCAI) should be confirmed in a variety of clinical settings.

We therefore conducted a systematic review with the objective of determining whether HHMT increases directly observed hand hygiene compliance among HCWs compared to usual care. Additional objectives were to determine whether HHMT reduces HCAI incidence or improves other measures of hand hygiene including hand hygiene frequency, volume of soap and ABHR use, or compliance as defined by the individual HHMT [i.e. system-defined compliance (SDC)].

Methods

This review is consistent with PRISMA and our protocol was registered with PROSPERO (CRD42013004519) and published.[4,6]

Search strategy

Medline, Embase, CINAHL, Web of Science, and the Cochrane Central Register of Controlled Trials were searched from inception until 31 December 2013 (see Appendix for search strategy).[4]

Eligibility criteria

The review included experimental and quasi-experimental studies of HHMT conducted in acute or long-term care that measured hand hygiene and/or HCAI incidence. Studies were excluded if the HHMT was installed solely to evaluate a non-HHMT-related intervention or if the study focused on hand hygiene at ward/hospital entrances or in the operating room. Only peer-reviewed, English language publications were included.

Data extraction and quality assessment

All steps in the selection, extraction and assessment process were performed independently by two authors (J.A.S., M.P.M.) (Figure 1). Data were abstracted on to a standardized template and discrepancies resolved by consensus. Abstracted data included information on the study setting, design, intervention, and outcomes. Quality was assessed using the Cochrane Effective Practice and Organization of Care Group Risk of Bias Assessment Tool for controlled trials and time series.[7] Quasi-experimental studies were assessed using a design hierarchy described by Harris *et al.*, with risk of bias assessed using the approach taken by Schweizer *et al.*[8,9]

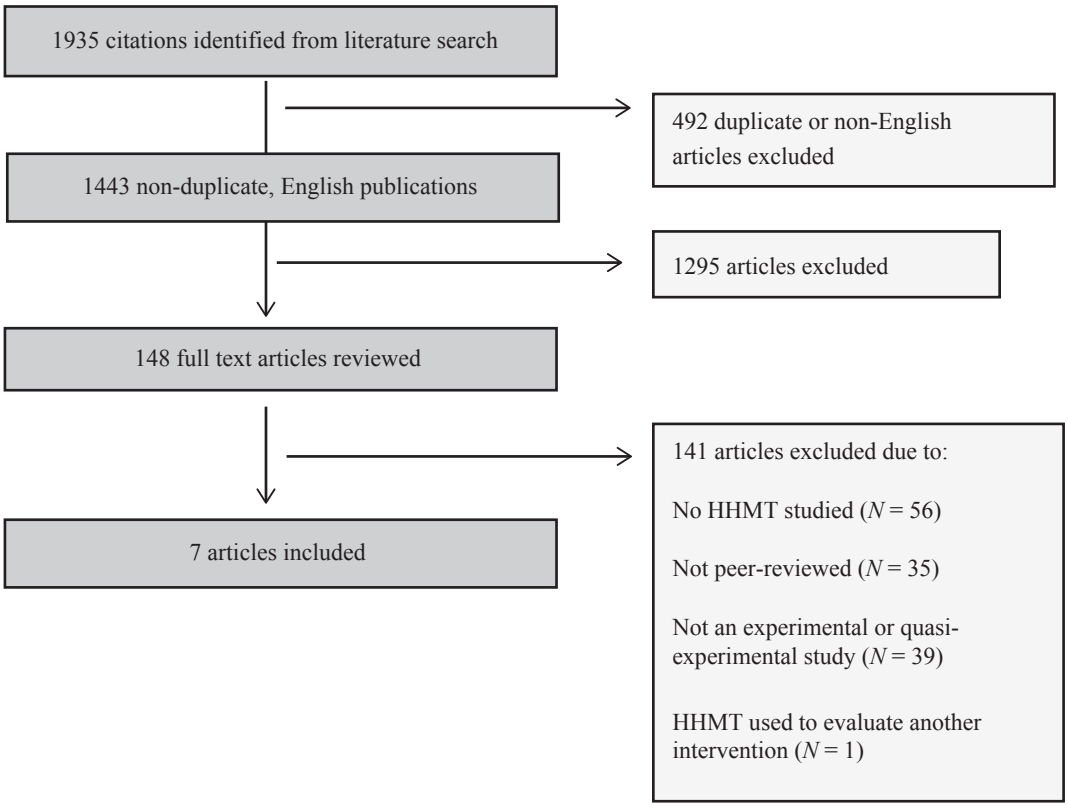

Figure 1. Study selection process. HHMT, hand hygiene monitoring technology.

Data synthesis

Summary tables of included studies were developed. Following the approach of the Economic and Social Research Counsel guidance report, we developed an *a priori* theoretical model for how HHMT might improve hand hygiene; described the outcomes of each study as related to our objectives; explored factors that might explain differences across studies; and assessed the strength of the evidence.[4,10]

Results

Search results

No study measured directly observed compliance. Seven studies met inclusion/exclusion criteria and measured one or more outcomes relevant to our secondary objectives (Figure 1).[9,11–17] Heterogeneity in design, intervention, and outcome precluded meta-analysis.

Overview of included studies

Most studies were conducted on a single ward (Table I). The median (range) duration was 24 (2–91) weeks and the median (range) number of hand hygiene opportunities observed was 194,150 (8235–1,017,600). The HHMT studied included electronic monitoring systems (EMS) that provided reminders for room exit and/or entry but no feedback ($N = 2$), EMS or video monitoring systems (VMS) that provided aggregate feedback ($N = 3$), and EMS that provided individualized feedback and real-time reminders ($N = 2$).

Primary outcomes were SDC ($N = 5$), hand hygiene frequency ($N = 1$), and both SDC and hand hygiene event rate ($N = 1$) (Table I). Except for two studies of the same VMS, no studies used the same outcome and no comparisons between EMS were possible. Only two studies were controlled. No study measured hand hygiene prior to the installation and activation of the HHMT, thus the impact of an HHMT-induced Hawthorne effect could not be evaluated. All quasi-experimental studies were at high risk of bias (Table II) whereas the risk of bias for the controlled trials and time-series analyses varied (Table III).

Characteristics and limitations of individual studies by type

Studies using HHMT that provides real-time reminders without feedback

Swoboda *et al.* used a pretest–post-test design with removed treatment to test an EMS on an intermediate care unit.[16] The EMS detected individuals exiting patient rooms and issued a voice prompt to perform hand hygiene. Instrumented ABHR and soap dispensers recorded hand hygiene events. Compliance was defined as a hand hygiene event recorded prior to (time-period not specified) or within 10 s of room exit.

During 15 months, 251,526 room exits were detected. Hand hygiene compliance at room exit increased 8.2% from the six-month monitoring phase to the six-month intervention phase (19.1% vs 27.3%, $P < 0.05$) and then fell to 24.4% during a three-month period after reminders stopped. No statistically significant reduction in nosocomial infections was observed.

Venkatesh *et al.* used an uncontrolled pretest–post-test design to assess an EMS on a haematology unit.[17] The EMS detected individuals entering or exiting the room and issued voice or sound prompts to perform hand hygiene. Instrumented ABHR dispensers recorded hand hygiene events. Compliance was defined as a hand hygiene event recorded prior to or after entry/exit, but the time-frame used was not provided.

During four separate periods, 8235 room entries/exits were detected. Hand hygiene at entry/exit increased 33.8% from two control periods of five and six days' duration to two intervention periods, each of seven days' duration, that occurred three and six months later (36.3–70.1%, $P < 0.05$). It was not clear whether the voice prompts remained active throughout the six-month study period or why data were not collected over the entire six months. No statistically significant decline in vancomycin-resistant enterococcus transmission rates was identified.

Both studies were at high risk of bias. These studies provide insufficient evidence to assess the potential for EMS with voice prompts to improve HCW hand hygiene.

Studies using HHMT that provides aggregate feedback without reminders

Marra *et al.* and Armellino *et al.* evaluated EMS/VMS that provided aggregate feedback without real-time reminders.[11,12,15] The studies by Armellino *et al.* are considered together as they used the same design and VMS, in a medical and then surgical intensive care unit (ICU). In both ICUs, video cameras were installed such that ABHR and soap dispensers were within sight of the cameras. The cameras recorded for 30 s whenever anyone entered or exited the room. Trained observers reviewed the video in near real-time. Compliance was defined as the proportion of times HCWs performed hand hygiene within 10 s prior to or after room entry/exit. Episodes in which HCWs were in the room for <60 s were excluded. Cumulative per-shift compliance was shown on a screen at the nursing station, and more detailed per-shift and weekly feedback were provided.

During the two studies, 432,482 and 136,773 room entries/exits were recorded. In the medical ICU, SDC on room entry/exit rose from 6.5% during 16 weeks of monitoring to 81.6% during the first 16 weeks of monitoring and feedback, and remained elevated at 87.9% for an additional 75 weeks. The time-series analysis demonstrated a significant and rapid increase in SDC when feedback started, with a trend towards declining compliance over the next 75 weeks. In the surgical ICU, SDC on room entry/exit was 30.4% during four weeks of monitoring, rose to 82.3% during 16 weeks of monitoring and feedback, and remained elevated at 83.2% for an additional 48 weeks. The results of the time-series analysis were not provided for the second study.

Marra *et al.* used a non-randomized, controlled trial design to evaluate an EMS on a step-down unit, using a second step-down unit as a control.[15] Instrumented ABHR dispensers were installed on both units to count hand hygiene events. Nurses on the intervention unit received twice-weekly feedback on hand hygiene frequency and nosocomial infection rates, with no feedback provided on the control unit. No baseline hand hygiene data were collected on either unit. Over a six-month period, there were 117,579 dispensing events on the intervention unit and 110,718 on the control unit. The difference of +6861 interventions in the intervention unit was not

Table I
Characteristics of included studies

Study	Study design	Study setting	Population	HHMT type	Events tracked	Movement tracking	Feedback	Real-time reminders	Outcomes	Compliance definition	Results
Swoboda *et al.*[16]	Pretest–post-test study	Intermediate care unit	All HCWs and visitors	Electronic	ABHR + soap	Room exit	No	Voice prompt	System defined compliance, nosocomial infection rate	Proportion of room exits with a hand hygiene event prior to or within 10 s of exit	P1 (monitoring): 19.1% P2 (monitoring + reminders): 27.3% P3 (monitoring): 24.1% P2 vs P1: +8.2%[a] P3 vs P1: +5%
Venkatesh *et al.*[17]	Pretest–post-test study	Haematology ward	All HCWs and visitors	Electronic	ABHR	Room entry/exit	No	Voice and sound prompt	System defined compliance, VRE transmission[b]	Proportion of room entries/exits with a hand hygiene event	P1 (monitoring): 36.3% P2 (monitoring + reminders): 70.1% P2 vs P1: +33.8%[a]
Armellino *et al.*[11]	Interrupted time-series	Medical ICU	All HCWs	Video	ABHR + soap	Room entry/exit	Aggregate, continuous	No	System defined compliance	Proportion of room entries/exits with a hand hygiene event prior to or within 1 s of entry/exit where time in room >60 s	P1 (monitoring): 6.5% P2 (monitoring + feedback): 81.6% P3 (monitoring + feedback): 87.9% P2 vs P1: +75.1%[a] P3 vs P1: +81.4%[a]
Armellino *et al.*[12]	Interrupted time series	Surgical ICU	All HCWs	Video	ABHR + soap	Room entry/exit	Aggregate, continuous	No	System defined compliance	As above	P1 (monitoring): 30.4% P2 (monitoring + feedback): 82.3% P2 vs P1: +51.9%[a]
Marra *et al.*[15]	Non-randomized, controlled trial	Step-down unit ($N = 2$)	All HCWs and visitors[c]	Electronic	ABHR	Not tracked	Aggregate, two/week[c]	No	Hand hygiene frequency, nosocomial infection rate	NA	Control (monitoring): 110,718[d] Intervention (monitoring + feedback): 117,579[d] Intervention vs control: +6861
Levchenko *et al.*[14]	Pretest–post-test study	Chronic care ward	14 nurses	Electronic	ABHR + soap	Room entry/exit	Individual, two/week	Vibration	System defined compliance, hand hygiene event rate	Proportion of room entries/exits with a hand hygiene event within 60 s prior to entry or 20 s prior to exit ('clean') or within 20s of vibratory reminder ('performed after prompt')	P1 (monitoring): 2.97[e] P2 (monitoring + feedback): 2.84[e] P3 (monitoring + feedback + reminders): 6.61[e] P2 vs P1: 0.13[f] P3 vs P1: +3.64[f]

Fisher *et al.*[13]	RCT	Two wards + surgical ICU	231 nurses	Electronic	ABHR	Zone entry/exit	Individual, one/week	Vibration	System defined compliance	Proportion of zone entries/exits with a hand hygiene event within 6 s of entry or 60 s of exit	Intervention (monitoring + feedback + reminders) vs Control (monitoring): +6.8%[a]

HHMT, hand hygiene monitoring technology; ABHR, alcohol-based hand rub; HCWs, healthcare workers; P, phase; VRE, vancomycin-resistant enterococcus; ICU, intensive care unit; NA, not applicable; RCT, randomized controlled trial.

[a] $P < 0.05$.

[b] Directly observed compliance may have been measured during the study but results were not presented.

[c] Outcome recorded for all HCWs and visitors but feedback only to nurses.

[d] Count of total hand hygiene events.

[e] Hand hygiene actions/h.

[f] *P*-value not reported.

statistically significant ($P = 0.63$). No difference in nosocomial infections was noted between the units.

The studies by Armellino *et al.* demonstrated a significant improvement in SDC at room entry/exit and are at moderate risk of bias.[11,12] The size and sustainability of the intervention effect is remarkable and suggests a significant impact of the VMS on HCW behaviour. However, it is possible that HCWs modified their behaviours in a manner that improved the SDC but would not have improved directly observed hand hygiene. For example, after receiving the feedback that compliance was 6.5%, HCWs may have started making briefer visits, ensured that hand hygiene was performed within 10 s of exit (rather than after 10 s) or avoided dispensers that were not on camera. It is also possible that the feedback provided to HCWs would have improved hand hygiene even without the use of a VMS. For example, if directly observed compliance rates were posted on the unit and staff received per-shift reminders from unit leadership about the importance of hand hygiene, improvement would likely have occurred without the expense of installing cameras. Use of a control group that received a similar intensity intervention but without video monitoring, combined with measurement of directly observed compliance on intervention and control units, would have definitively established whether the VMS improved hand hygiene.

The study by Marra *et al.* is limited by the lack of baseline data. Although both units were similar in size and patient mix, hand hygiene can vary from unit to unit.[18] Unless it is known that hand hygiene frequency on both units was similar at baseline, the observed result of no difference between units could be consistent with the intervention improving or worsening hand hygiene.

In summary, these results provide preliminary evidence suggesting that use of VMS to provide feedback on SDC may lead to rapid changes in HCW behaviour and sustained improvements in SDC. It will be important to confirm these results in other settings and ensure that changes in SDC are associated with improvement in hand hygiene practices that would be expected to reduce the incidence of HCAI.

Studies using HHMT that provided both individual feedback and real-time reminders

Levchenko *et al.* and Fisher *et al.* evaluated HHMT that linked hand hygiene data to individual HCWs, allowing for individual feedback and real-time reminders.[13,14] A pretest–post-test study by Levchenko *et al.* recruited 14 nurses on a chronic care ward to test an EMS.[14] The EMS consisted of instrumented ABHR and soap dispensers that recorded hand hygiene events, zone monitors that detected room entry/exit and a monitoring device worn by participants that recorded room entries/exits and hand hygiene events and issued reminders. Reminders took two forms — a green light on the monitoring device that turned on for 60 s following a hand hygiene event and a vibratory prompt that occurred if the HCW entered/exited a room without performing hand hygiene. The study measured hand hygiene event rate (i.e. hand hygiene dispensing events per hour) and hand hygiene opportunity rate (i.e. hourly rate of monitored HCW entering or exiting room). They then classified hand hygiene opportunities as 'clean' (hand hygiene performed within 60 s preceding room entry or 20 s preceding room exit), 'performed after prompt' (hand hygiene event performed within 20 s of prompt and prior to subsequent room entry/exit) and 'ignored after prompt' (no

Table II
Risk of bias: quasi-experimental studies

Criteria	Swoboda *et al.*[16]	Ventkatesh *et al.*[17]	Levchenko *et al.*[14]
Did the study attempt to avoid bias and control for confounding?	H	H	H
Was the study successful at avoiding bias and controlling for confounding?	H	H	H
Did the study include an appropriate control or comparison group?	H	H	H
Were the operational definitions or description of the interventions clear?	H	H	U
Was the statistical analysis adequate?	H	H	H
Was adherence to the intervention monitored?	H	H	H
Justification of the use of a quasi-experimental design	H	H	H
Use of correct nomenclature to describe the quasi-experimental design	L	H	H
Recognition of possible limitations of the quasi-experimental design	L	H	H

H, high risk of bias; L, low risk of bias; U, unclear risk of bias.

hand hygiene within 20 s of prompt or no hand hygiene prior subsequent room entry/exit). Individual feedback was provided twice during the study.

In total, 31,400 room entries/exits were detected. During an initial 1270 h of monitoring, there were 2.97 hand hygiene actions per hour and 8.92 hand hygiene opportunities per hour. During the intervention phase that included feedback and vibratory reminders, there were 6.61 hand hygiene actions per hour and 9.56 opportunities per hour. SDC (proportion of opportunities classified as 'clean' or 'clean after prompt') was presented in graphical form and showed an increase from ~25% during the monitoring phase to ~65% during the intervention phase.

The study by Fisher *et al.* was a randomized controlled trial (RCT) of an EMS conducted on three wards at two hospitals and involving 233 HCWs.[13] Instrumented ABHR monitors recorded hand hygiene events and receivers detected HCW entry/exit into a 'zone' around the patient bed. Participants wore a monitoring device that recorded their hand hygiene events and room entries/exits and allowed provision of individual feedback and real-time reminders. Compliance was defined as an ABHR event performed within 6 s of entering or 60 s of exiting a patient zone. Consumption of ABHR was also monitored.

The study consisted of a 14-week monitoring phase, after which participants were randomized. The intervention consisted of a six-week phase of monitoring and real-time reminders followed by four weeks of monitoring, real-time reminders, and weekly individual feedback. The control group was monitored throughout, without feedback or reminders. There were 221 participants eligible for the analysis and 1,017,600 zone entries/exits detected during the study. Baseline SDC on zone entry and exit for the intervention group was 28% and 28%, respectively; during the final phase of the study, compliance on zone entry and exit was 28% and 33%, respectively. Despite these minimal changes, multivariate analysis demonstrated a statistically significant 6.8% higher compliance in the intervention vs the control arm, partially attributable to a drop in compliance in the control arm. ABHR usage apparently paralleled these trends but data were not provided.

These studies provide conflicting evidence regarding the efficacy of EMS capable of providing individual feedback and real-time reminders, with the study at lowest risk of bias demonstrating minimal benefit.

Discussion

Hand hygiene improvement is challenging and HHMT offers great promise. However, its efficacy in improving compliance has not been systematically assessed.

Unfortunately, our systematic review did not identify any HHMT study that measured directly observed compliance.

Table III
Cochrane EPOC Risk of Bias Assessment Tool: controlled clinical trials and interrupted time series

Criteria	Marra *et al.*[15]	Fisher *et al.*[13]	Armellino *et al.*[11]	Armellino *et al.*[12]
Random sequence generation	H	L	–	–
Allocation concealment	H	U	–	–
Baseline outcome measurements	U	L	–	–
Baseline characteristics	L	H	–	–
Contamination	U	U	–	–
Intervention independent of other changes	–	–	L	L
Pre-specified shape of intervention effect	–	–	L	L
Intervention unlikely to affect data collection	–	–	U	U
Incomplete outcome data	U	U	L	L
Knowledge of allocated interventions	U	L	U	U
Selective outcome reporting	H	L	L	H
Other risk of bias	L	L	U	U

H, high risk of bias; L, low risk of bias; U, unclear risk of bias; –, not applicable.

Table IV
Suggested design for future efficacy trials of hand hygiene monitoring technology (conducted after pilot studies demonstrating feasibility and possible impact on hand hygiene)

Aspect of study	Recommendation	Rationale
Setting and population	Systems should be tested in multiple healthcare settings	Ensure effectiveness in different contexts including acute and long-term care, different healthcare worker and institutional cultures, different physical layouts, single vs multi-bedded rooms, etc.
Design		
Recommended	RCT (e.g. for systems with individual feedback or reminders) or cluster RCT; ITS with control arm; stepped wedge design	All contain elements to remove or limit bias and confounding including randomization and/or the use of a control group
Exploratory	Pretest–post-test design with repeated treatment with or without control group	Repeated treatment mitigates against confounding, although this design remains at a higher risk of bias than those discussed above; may be appropriate for initial pilot testing
Intervention	Describe intervention in sufficient detail to be reproducible; for feedback interventions, define the frequency of feedback, the type of feedback, and who provides the feedback	Impact of feedback may vary depending on intensity and frequency; response may differ for written and electronic communications and for face-to-face communications; feedback may have different impact if anonymous or when coming from a research team, peer, or supervisor
	Consider testing different mechanisms of action separately or sequentially (e.g. Hawthorne effect vs impact of feedback vs impact of reminders)	Will allow determination of mechanism by which hand hygiene compliance is improved, and thus which elements are essential for an effective HHMT
Outcome	Use one or more validated outcomes independent of the system (i.e. other than the system-defined compliance)	Allows comparison between different EMS/VMS that have different definitions of compliance
	Measure directly observed compliance	Considered the current 'gold standard' despite limitations and is the only metric that considers healthcare worker contact with patients or their environment
	Measure dispenser count data from all dispensers on intervention and control units	Provides objective data on frequency of hand hygiene events that should not be subject to Hawthorne effect if healthcare workers unaware that dispensers are instrumented, and can be compared between systems that use different definitions of compliance
	Collect data prior to installation of the EMS/VMS and/or before healthcare workers are aware of EMS/VMS to obtain a true baseline	Data collected during the 'baseline' period of most EMS/VMS studies may overestimate baseline compliance if healthcare workers believe they are already being monitored (i.e. Hawthorne effect)
	Collect data for sufficient duration in each study phase to ensure appropriate sample size, allow healthcare workers to become familiar with feedback and other interventions; and to ensure sustainability of the effect. Suggest minimum of three months per phase and minimum of 12 months of data collection	Healthcare workers may not understand or trust feedback initially but may need some time to become accustomed to the system and its feedback and reminders. An initial increase in compliance may be due to the Hawthorne effect and/or due to increased discussion/education/awareness of hand hygiene at the time of installation and training, and these effects may wane over time
	If HCAI is used as an outcome measure, the HCAI(s) of interest should be defined *a priori* and the study should be appropriately powered to detect a difference in HCAI	Reducing HCAI is the objective of EMS/VMS. However, selective reporting bias can occur if reductions in HCAI or ARO are reported *post hoc*, particularly if the HCAI/ARO demonstrating the largest response is selected; most EMS/VMS studies are unpowered to detect differences in HCAI/ARO

(*continued on next page*)

Table IV (*continued*)

Aspect of study	Recommendation	Rationale
Co-intervention	If training, education or awareness efforts are required for the intervention group, a similar intensity of hand hygiene intervention should be applied to the control group	This approach ensures that any detected difference between control and intervention arms is not due to hand hygiene education or training unrelated to the EMS/VMS itself
	Non-technological efforts to improve hand hygiene on baseline and control units should be described	To ensure that there are no differential activities applied only to the intervention unit, other than the EMS/VMS under study, that could account for difference in compliance
Confounding	Variables potentially associated with both the intervention and the outcome should be reported	For example, if a large outbreak associated with poor patient outcomes occurred on the intervention unit prior to installation, it may be that the EMS/VMS was installed as a response to the outbreak, and thus improvements in hand hygiene occurred because of the outbreak, or reduction in HCAI occurred because of regression to the mean.

RCT, randomized controlled trial; ITS, interrupted time series; HHMT, hand hygiene monitoring technology; EMS, electronic monitoring system; VMS, video monitoring system; HCAI, healthcare-associated infection; ARO, antibiotic-resistant organisms.

Direct observation is a flawed metric but it is still the only measure that directly links hand hygiene events to HCW contact with patients or their environment — the presumed mechanism by which pathogens are transmitted and the theoretical basis for hand hygiene efficacy.[19–21]

We did, however, identify seven studies that met secondary inclusion criteria. Most studies relied on SDC as their outcome, precluding comparisons between HHMT and preventing an assessment of the Hawthorne effect, as this requires that the outcome be measured before and after HCWs are aware of being monitored. Classification of HHMT by presumed mechanism of action identified three groups: EMS that provides reminders without feedback; EMS/VMS that provides aggregate feedback without reminders; and EMS that provides individual feedback and reminders.

The two studies evaluating EMS with reminders only were limited by their design and at high risk of bias (Table II). Although both showed some increase in SDC, no conclusions regarding the efficacy of this type of system could be made. Further evaluation of these HHMTs using stronger study designs (Table IV) is merited, as these are simple and relatively inexpensive HHMTs.

Of the three studies of EMS/VMS with aggregate feedback, only the two VMS studies were interpretable. These VMS studies demonstrate a sharp and sustained increase in SDC when feedback was activated and were at moderate risk of bias due to the lack of a control group, definition of compliance used, and potential for unmeasured confounders and co-interventions. Generalizability is an issue as the studies were conducted at a single hospital. Additional concerns are the cost of monitoring and the privacy of patients and HCWs.[1,2,5] However, the strongly positive results suggest that testing at additional sites using a stronger study design (Table IV) should be prioritized.

Finally, complex EMSs that provide individual feedback and real-time reminders would seem, *a priori*, to have the greatest potential to impact compliance as they exploit all potential mechanisms for improvement. Despite this, the two identified studies showed conflicting results, with the RCT at low risk of bias showing no clinically significant impact of the system. This technology still holds promise but we believe these results should dampen hospitals' enthusiasm for adopting expensive EMS outside of the research context.

Recommendations for future HHMT trials

This review has identified several methodological flaws in the existent studies of HHMT and has therefore endeavoured to make recommendations to inform the design of future HHMT efficacy studies (Table IV). Our comments are focused on HHMT that have already been pilot-tested for feasibility, HCW acceptance and accuracy, and are ready for efficacy testing in a real clinical environment. Whereas many of these recommendations (e.g. randomization, use of a control arm) apply widely to medical research, there are some nuances to studies of HHMT that need highlighting.

First, it appears that testing HHMT in a variety of different settings is essential. The success of HHMT may depend on both the physical structure and organizational culture of the implementing unit(s). Second, many HHMT include a feedback component. The success of feedback may vary depending on a variety of factors including: who provides the feedback, the medium used (e.g. email vs face-to-face meeting), and the specific content. Studies of HHMT with feedback should provide a detailed description of all aspects of the feedback supplied. A related issue is that feedback is often packaged with educational messages or HCAI feedback that could be provided without data from HHMT; it is therefore essential that control groups should receive a similar intensity of feedback, but without specific data generated by HHMT, to ensure that improvements are due to the HHMT itself. Study duration is also important for interventions aimed at changing behaviour as the initial impacts may decrease as the excitement over the initial implementation of new technology fades, alarm or feedback fatigue sets in, or the impact of the Hawthorne effect dwindles.

The selection of the correct outcome(s) is of particular importance. All HHMT trials should include, in addition to SDC, two system-independent measures of hand hygiene, including directly observed hand hygiene compliance measured using a

validated definition and an additional measure. System-independent measures are the only outcomes that would allow a complete assessment of the impact of HHMT (including Hawthorne effect) and comparison between different HHMT. Using a simple EMS (i.e. event counter) may be an ideal way to evaluate both VMS and more complex EMS, as, unlike direct observation, it is objective and reproducible, and can be compared between studies.[19,20] If in a specific study SDC rises but direct observation remains unchanged, it may be difficult to know which is more reflective of the true status of 'hand hygiene'. However, if count data were available, it could help resolve such discrepancies.

HCAI incidence is also an important outcome to consider given that reducing HCAI incidence is the primary goal of all hand hygiene improvement efforts. Currently, however, most HHMT trials are underpowered to detect differences in HCAI and, in many cases, they appear to have selected outcomes to report *post hoc*. We therefore favour using hand hygiene metrics as the primary outcome of initial HHMT trials, unless a cluster RCT sufficiently powered for an HCAI outcome is conducted and specific HCAI(s) to be measured are defined *a priori*.

This systematic review has several limitations. Non-English publications were not included. There is a considerable risk of publication bias, as many studies are industry-funded. This would be a larger issue if more high-quality, positive studies had been identified and may become a problem in the future. Thus, whereas publication bias may exist, it likely affected the quantity of the studies identified rather than the qualitative nature of the results.

In summary, insufficient evidence was found to recommend adoption of HHMT in general, or any specific HHMT, as a hand hygiene improvement strategy. Limited data suggest that future research studies should prioritize use of VMS; however, EMSs also merit additional testing. Future trials should include stronger designs, control groups, and system-independent measures of hand hygiene.

Conflict of interest statement
Dr Fernie is a biomedical engineer and one of the studies included in the review was conducted by his research team. Dr Fernie's role in the review was limited to the provision of expertise on the technical aspects of HHMT functionality, and he was not involved in decisions regarding study inclusion or quality assessment. The other authors have no potential conflicts of interest to declare.

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Appendix. Medline search strategy

1. exp Iatrogenic Disease/
2. exp Cross Infection/
3. nosocomial.mp.
4. iatrogenic$.mp.
5. exp Vancomycin Resistance/
6. VRE.mp.
7. exp Methicillin-Resistant Staphylococcus aureus/
8. mrsa.mp.
9. exp hand/
10. hand.mp.
11. or/1–10
12. exp infection control/
13. pc.fs. [prevention and control as a floating subject heading]
14. exp anti infective agents/
15. exp Decontamination/
16. disinfect$.mp.
17. or/12–16
18. 12 and 17
19. exp hand hygiene/
20. (hand adj2 wash$).mp.
21. (hand adj2 hygiene$).mp.
22. (hand adj2 clean$).mp.
23. (hand adj2 sanitiz$).mp.
24. (hand adj2 disinfect$).mp.
25. or/19–24
26. 18 or 25
27. exp population surveillance/
28. surveillance.mp.
29. monitor$.mp.
30. feedback.mp.
31. alarm.mp.
32. or/27–32
33. 26 and 33
34. exp automation/ [includes MeSH robotics]
35. automated system.mp.
36. automatic$.mp.
37. sensor$.mp.
38. RFID.mp.
39. exp Radio Frequency Identification Device/
40. exp Electronics/
41. exp Video-Audio Media/
42. (monitor adj2 computer$).mp.
43. (monitor adj2 video$).mp.
44. (monitor adj2 electr$).mp.
45. (system$ adj2 computer$).mp.
46. (system$ adj2 video$).mp.
47. (system$ adj2 electr$).mp.
48. exp tape recording/ [includes Videotape Recording]
49. computer.ti,ab.
50. video.ti,ab.
51. exp computer systems/
52. or/35–48
53. 34 and 53
54. remove duplicates from 55

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