Lau *et al. Antimicrobial Resistance & Infection Control* (2026) 15:27
https://doi.org/10.1186/s13756-025-01679-3

Antimicrobial Resistance & Infection Control

RESEARCH

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Evaluating hand hygiene compliance: a digital-based approach for assessing healthcare worker practices in the teaching hospitals in Malaysia

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Abstract

Background Hand hygiene compliance among healthcare workers (HCWs) remains a critical challenge in infection prevention. Traditional audit methods have limitations, including observation bias and Hawthorne effect. This study used eye-tracking technology to as an objective behavioural tool to assess and compare of HCWs compliance with infection control measures in two teaching hospital in Malaysia.

Methods A prospective observational study was conducted across two hospitals (Hospital I and II). Participants performed standardized patient care scenarios incorporating the "5 Moments for Hand Hygiene" technique while wearing eye-tracking glasses to monitor the compliance of HCWs. Handrub duration, scrub-the-hub duration and gaze behavior including dwell time, fixation time and saccade on selected areas of interest were recorded.

Results 75 HCWs (doctors and nurses) were recruited. Hospital I showed higher overall compliance (56.9%) than Hospital II (42.6%). Lowest adherence occurred at the moment "before patient contact". The average handrub duration of 13.63 s fell substantially below the WHO-recommended standard. Similarly, scrub-the-hub durations of 7.6 s in Hospital I and 4.13 s in Hospital II failed to meet the 10–15 s guideline, potentially compromising the effectiveness of these critical infection control measures. Medical station alcohol-based handrub (ABHR) dispensers received more visual attention than bedside ABHR, but did not consistently translate to compliance. Scrub-the-hub required the longest visual engagement, indicating procedural complexity.

Conclusions The use of eye-tracking technology in hand hygiene audits identified critical gaps in both compliance and technique quality. This study suggests the need for targeted training on proper durations, optimized ABHR

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placement, and technology-enhanced monitoring. This approach provides behavioral insights that could improve hand hygiene interventions and reduce infection risks.

Keywords Eye-tracking, Hand hygiene compliance, Infection prevention, WHO 5 moments, Healthcare workers

Introduction

Hospital acquired infections (HAIs) due to Multidrug-resistant organisms (MDRO) is considered the biggest threat to the healthcare system [1–3]. MDRO can be transmitted through direct or indirect contact between patients and may be disseminated widely within healthcare settings in the absence of proper infection control measures. Healthcare environment, medical devices and healthcare providers are potential vehicles for the transmission of pathogens in hospitals [4]. Particularly, healthcare workers' hands are the main pathway through which pathogens are transmitted, leading to HAIs. Hence, hand hygiene is regarded as the fundamental practice for minimizing HAI. Despite ongoing hand-hygiene campaigns and considerable efforts invested by the hospital management to prevent transmission and reduce HAI, the current knowledge, attitude and compliance levels of HCWs regarding infection control practices remain unclear.

In 2005, the World Health Organization (WHO) launched the 'First Global Patient Safety Challenge' with the theme "Clean Care is Safer Care" to enhance patient safety in healthcare settings through a comprehensive strategy, including hand hygiene improvement and the use of ABHR at the point of care [5]. In 2009, WHO further advanced this effort to reduce HAI by introducing the "5 Moments for Hand Hygiene" framework [6, 7]. Most HCWs understand the importance of hand hygiene during their daily routine. However, knowing the importance of hand hygiene doesn't always translate into consistent practice among HCWs. Various approaches have been employed to improve hand hygiene, including direct observation by trained auditors. The WHO 5 moments hand hygiene technique, using the standardized WHO hand hygiene observation form, is widely used in hospital to monitor hand hygiene compliance among HCWs [8]. However, these activities are labor intensive and may cause the Hawthorne effect during regular hand hygiene observation.

The implementation of an electronic device to monitor hand hygiene practice presents a straightforward yet innovative solution to address the limitations and manpower constraints. Eye tracking offers valuable insights into the behavioral aspects of hand hygiene, such as frequency and technique, and enables comprehensive monitoring of hand hygiene compliance across various settings and scenarios. This technology has been utilized to observe the practice of HCWs during their routine patient care and to study the movements of eyes during a range of activities to provide a better understanding of the cognitive processes [9, 10]. It could overcome the observation bias during audit and reveal information that conventional observation normally misses.

Eye-tracking technology has been increasingly explored in healthcare to study clinical decision-making, situational awareness, and procedural performance. It has also been widely used in nursing research to evaluate the cognitive processes and visual attentions [11]. However, its application in infection prevention and control (IPC) remains limited. Previous studies have used wearable eye-tracking devices to compare hand hygiene behaviours under different dispenser placement, and reported useful and reliable gaze metrics (dwell time, fixation duration, revisits to key regions such as dispensers) to support assessments of hand hygiene compliance [12]. These findings demonstrate that visual attention metrics can complement conventional compliance audits by revealing cognitive factors influencing adherence. The present study builds upon these findings by employing eye-tracking as an objective behavioural tool to assess and compare of HCWs' compliance with infection control measures in two teaching hospitals in Malaysia.

Methodology

Study design and population

This study was conducted in a teaching ward at the Universiti Malaya Medical Centre (UMMC) and the Hospital Sultan Abdul Aziz Shah (HSAAS), respectively, indicated as Hospital I and Hospital II. These two teaching hospitals were selected due to their distinct differences in the year of establishment, allowing for a comparative analysis of how generational differences impact various aspects of hospital performance. Hospital I, established in 1962, is a major teaching hospital with 1600 beds, representing a long-standing pioneer teaching hospital in Malaysia. Whereas Hospital II, with a capacity of 400 beds, was established more recently in 2020 represented as a modern teaching hospital.

The inclusion criteria were full-time HCWs, who are nurses or doctors, aged 18 years old and above, working at the chosen hospitals. Participants who wore spectacles were excluded from this study to avoid calibration problems. HCWs were recruited via email and word-of-mouth on a voluntary basis. All participants were given written informed consent and study information sheet prior to the test. As a token of appreciation for their time and participation in this study, all HCWs who completed the eye-tracking hand hygiene assessment received a modest honorarium. The honorarium was not performance-linked and was provided uniformly to all participants after completion, solely to compensate for their time and inconvenience during data collection. To minimize bias, the participants were blinded to the study's aim, and did not receive any additional training specifically for the purpose of the study. All participating hospitals implement mandatory annual IPC training, including hand hygiene and aseptic technique modules. Hence, participants were presumed to have received comparable baseline education prior to the study. Participants' demographic were collected and divided into different categories based on working experience, age group, hospital and position.

Procedure

A scenario incorporating the "5 Moments Hand Hygiene" technique was designed based on the WHO hand hygiene guideline[13] by the Infection Control experts in both hospitals. The details of each scenario and Areas of interest (AOIs) are listed in Table 1. During the scenario, nurses and doctors were required to wear eye-tracking glasses—Pupil invisible (Pupil Labs, Berlin, Germany), while performing the task. Eye-tracking technology has demonstrated acceptable reliability for assessing hand hygiene compliance [12]. The Pupil invisible (Pupil Labs, Berlin, Germany) provides robust gaze estimation in real-world conditions with average uncalibrated accuracy of 4.6º and its high sampling rate (200 Hz for eye cameras) helps capture hand movement and gaze changes with reasonable temporal resolution, enabling precise measurement of visual attention and action timing, although with some margin of error [14].

Table 1 Details of the scenario and moment created

Scenario	Details of hand hygiene that need to perform	Details of 5 moments	AOIs
(1) The Doctor/Nurses need to ask patient's name by checking the medication form and the patient's identification wrist band	HCWs should perform Hand Hygiene (1) using ABHR before attending to the patient. Ask and clarify patient name by checking patient wrist band	The moment before patient contact	Handrub before patient Wristband
(2) Then leave the patient area to prepare medication	HCWs should perform Hand Hygiene (2) using ABHR after touching a patient. Then leave to prepare medication for that patient	The moment after touching patient	Handrub after touching patient
(3) Doctor / Nurses need to give IV medication as prescribed in the form through peripheral line	Give IV medication through a peripheral line and perform scrub-the-hub. Hand Hygiene (3) using ABHR should be performed immediately before administering medication	The moment before aseptic technique	Handrub before aseptic procedure Peripheral line/hub during scrub hub
(4) Leave the patient after medication	After giving medication, HCWs should perform Hand Hygiene (4) using ABHR immediately	The moment after body fluid exposure risk	Handrub after body fluid
(5) Then turn off the light switch as requested by patient	Suddenly, the patient asks to turn off the light switch. HCWs should perform Hand Hygiene (5) using ABHR after leaving the patient's surroundings	The moment after touching patient's surrounding	Light switch Handrub after patient surrounding

Hand hygiene compliance was independently assessed using two approaches: (i) conventional direct observation conducted in real time during the simulation, and (ii) post-session video annotation of eye-tracking recordings. Each method was performed by a separate group of trained auditors to avoid cross-contamination of data. The same hand hygiene events were analyzed using both methods to ensure accuracy and contextual validation. Direct observations were recorded using WHO's "5 Moments for Hand Hygiene" checklist, while eye-tracking videos were reviewed frame-by-frame to confirm each observed hand hygiene action and to examine participants' gaze behaviour and timing. Both groups underwent structured training using standardized criteria and reference examples before data collection.

Before the test began, trained personnel assisted participants in configuring the device and conducted a nine-point calibration for each participant to ensure high gaze estimation accuracy. To optimize tracking performance, participants were advised to remove eye makeup, while spectacle wearers were encouraged to wear contact lenses during the test. Each session took place individually in a private simulated ward, where two hand sanitizer stations were placed—one at the medical station and the other beside the patient's bed. A few AOIs were identified for each scenario. The eye-tracking terminology used in this study is defined in Table 2.

Firstly, the participants were briefed about the study and scenario by a trained personnel. Each participant was then provided with an inpatient medication Kardex to complete after administering the IV medication, as outlined in the scenario. The eye-tracking glasses began recording as soon as the session started and stopped once the participant exited the ward. During the session, trained auditor conducted a direct hand hygiene audit using standardized WHO observation forms [8]. To minimize bias and the Hawthorne effect, HCWs were not informed that they were being audited. A missed opportunity is defined as a situation where an indication for

Table 2 Definitions of eye-tracking terms used in this study

Terms	Definitions
Areas of interest (AOIs)	A specific predefined stimulus, element or region within a visual scene that researchers identify as significant for analysis
Dwell count	Number of times a respondent's gaze enters a specific AOI
Dwell times	Total duration of a respondent's gaze remains within a specific AOI
Fixation count	Total number of fixations detected within a specific AOI
Fixation duration	The average or cumulative time a respondent spent fixating within an AOI
Saccade count	The number of saccadic eye movements occurring during a task within an AOI

Table 3 Participants' demographic

Descriptions	Hospital I (n = 39)	Hospital II (n = 36)	Total (n = 75)	*P*-value
Gender				0.310
Male	7 (17.9%)	10 (27.8%)	17 (22.7%)	
Female	32 (82.1%)	26 (72.2%)	58 (77.3%)	
Age (mean)	28.55	32.33		
Age group				0.522
< 35 years' old	29 (77.4%)	29 (80.6%)	58 (77.3%)	
≥ 35 years' old	10 (25.6%)	7 (19.4%)	17 (22.7%)	
Position				0.701
Doctors	9 (23.1%)	7 (19.4%)	16 (21.3%)	
Nurses	30 (76.9%)	29 (80.6%)	59 (78.7%)	
Working experience				0.012*
≤ five years	22 (56.4%)	10 (27.8%)	32 (42.7%)	
> five years	17 (43.6%)	26 (72.2%)	43 (57.3%)	

**P*-value < 0.05

hand hygiene occurs but is not followed by the appropriate hand hygiene action [8].

Each session lasted approximately 3 to 6 min, during which hand hygiene compliance rates were recorded and compared across different HCW categories. The eye-tracking videos and data were securely stored and backed up in Pupil Cloud (https://cloud.pupil-labs.com/). The raw data were then imported into iMotions software (iMotions Module-Core and iMotions Module-Eye Tracking Glasses, Copenhagen, Denmark) for processing and analysis. Each video was labeled according to the participant's unique ID. Markers and AOIs were keyed in into the software before video annotation.

Each video was then annotated manually and validated by trained auditors. The compliance of handrub, handrub duration, scrub-the-hub duration, number of fixations, fixation duration, dwell time, dwell count and saccade count on areas of interest were recorded. The duration of each hand hygiene action was determined solely from the eye-tracking video recordings captured by the Pupil Invisible system (30 frames per second) [14]. For example, start and end points were defined as the first visible contact of the hands with the handrub dispenser and the completion of rubbing motion, respectively. All recordings were annotated frame-by-frame by two independent auditors using time-stamped video data. However, a minor degree of discrepancy may occur due to the manual annotation process.

A threshold of 75% was set as an indicator of good compliance in this study. This threshold was selected based on the national KPI as well as the threshold set by Malaysian patient safety goals[15]. According to WHO guidelines, the minimum recommended duration for performing ABHR is 20–30 s [13]. Whereas scrub-the-hub duration was recommended to be performed in 10–15 s by The Joint Commission[16].

After analysing with iMotions software, all the eye tracking data were analyzed by using IBM SPSS ™ Statistic software, version 28. Categorical variables were analyzed using Fisher's exact test or chi-square test, while continuous variables were assessed via Student's t-test or Mann–Whitney U test, depending on data normality.

Results

Participants demographic

A total of 75 HCWs participated in the eye-tracking hand hygiene study, comprising 39 participants from Hospital I (9 doctors, 30 nurses) and 36 participants from Hospital II (7 doctors, 29 nurses). Most participants were female (77.3%) within an age group below 35 years' old (78.4%). Among the HCWs, 42.7% had five or fewer years of working experience. However, a higher proportion (72.2%) of HCWs in Hospital II had more than five years of experience compared to those in Hospital I. A detailed demographic characteristics of the participants from both hospitals are presented in Table 3.

The eye-tracking videos were systematically annotated in the iMotions software according to the WHO's "5 Moments for Hand Hygiene" guideline by the Infection Control experts. A sample first-person perspective from the eye-tracking glasses is displayed in Fig. 1.

Hand hygiene compliance among HCWs was assessed based on the opportunities created during the patient care scenarios, in alignment with the "5 Moments for Hand Hygiene" framework [13]. Although each participant performed the same scenario or task, variation in individual workflow and patient interactions led to differences in the number of hand hygiene opportunities encountered. The total opportunities created, and the hand hygiene compliance based on WHO "5 moments of Hand Hygiene", including before patient (BP), before aseptic procedure (BA), after exposure to body fluid (ABF), after patient (AP), and after patient surrounding (APS) were recorded.

Fig. 1 Participants view from the eye-tracking glasses. *The yellow circle and line indicate the participants fixation and gaze motion

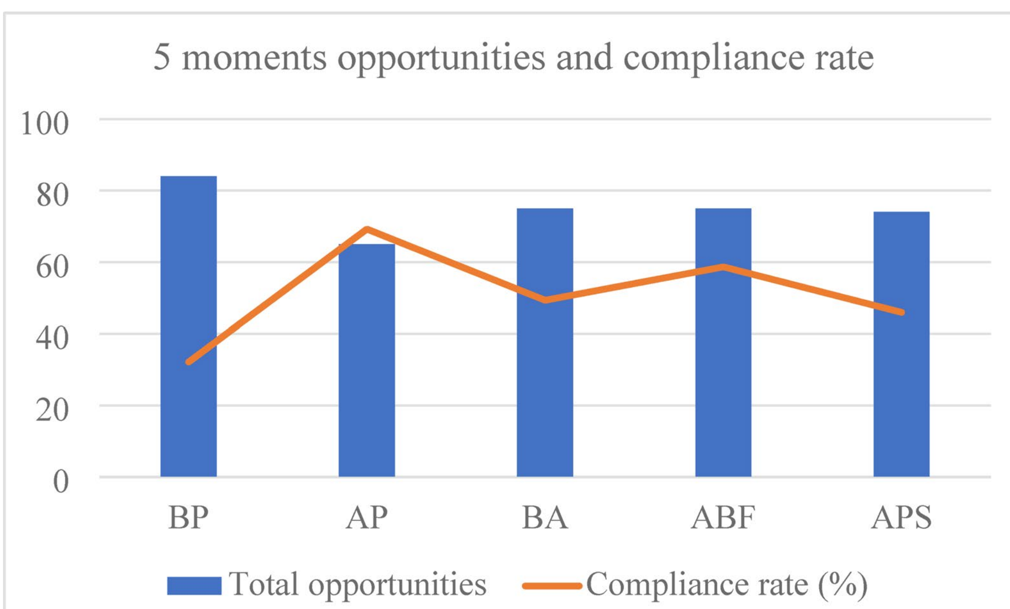


Fig. 2 Overall opportunities and compliance rate to the "5 Moments for Hand Hygiene"

Hand hygiene compliance rate based on eye-tracking analysis

The hand hygiene compliance rates and the total number of opportunities created by the HCWs are shown in Fig. 2. Overall, the highest number of opportunities occurred at the moment "before patient"; however, the highest compliance rate was observed at the moment "after patient contact". Compliance rates obtained from eye-tracking video annotation matched those recorded by direct observation, as both analyses were based on the same set of observed hand hygiene events. The eye-tracking data offered additional insights into gaze behaviour, visual attention, and the timing of hand hygiene actions. The average handrub duration recorded by the HCWs was 13.63 s, ranging from 1.93 to 28.08 s. Twenty out of 148 HCWs showed a compliance rate beyond 75%.

The comparative analysis of hand hygiene compliance between the two hospitals revealed notable differences in adherence to protocols. Based on the collected data (Table 4), Hospital I demonstrated better overall compliance at 56.9% compared to Hospital II's 42.6%. While both institutions showed their highest compliance rates after patient contact, they shared a common weakness in the "before patient contact" moments, which recorded the lowest adherence levels. A particularly notable difference was observed in compliance after contact with patient surroundings, where Hospital I outperformed Hospital II (55.3% vs 36.1%). In terms of technique quality, Hospital I recorded longer average handrub durations (10.72 s versus Hospital II's 7.96 s) and scrub-the-hub durations (7.60 s compared to 4.13 s in Hospital II).

Hand hygiene compliance rates in each moment were also analyze based on hospital affiliation, professions, working experience, age group and gender (Table 4). Univariate analysis showed hospitals (*P*-value = 0.107), professions (*P*-value = 0.930), gender (*P*-value = 0.666), working experience (*P*-value = 0.872), or age groups (*P*-value = 0.075) were not significantly associated with hand hygiene compliance. However, in the multivariate linear regression model consisting of x, y, z, age group was a significant predictor of hand hygiene (95% CI [1.41, 46.10], *P*-value = 0.041). Older age group had on average a 23.8% higher compliance rate compared to those in the younger age group.

Doctors in Hospital II demonstrated substantially higher compliance rates (62.2%) compared to their counterparts in Hospital I (43.9%). Notably, while nurses in Hospital I showed better adherence than doctors, this trend reversed in Hospital II where doctors outperformed nurses. The data also indicate that female HCWs, older practitioners, and those with more experience generally maintained higher compliance rates, suggesting these factors may positively influence hand hygiene practices.

Analysis of the association between sociodemographic factors and compliance rates ≥ 75% revealed several key findings (Table 4). Age emerged as a significant factor, with older HCWs demonstrating substantially better adherence. 52.9% of HCWs aged 35 years or older achieved good compliance, compared to their younger counterparts.

Among the entire cohort of 75 participants, only 20 (26.7%) met the 75% compliance standard. This high-performing subgroup was predominantly composed of practitioners from Hospital I, nursing staff, female HCWs, individuals with more than 5 years of clinical experience, professionals aged above 35 years.

Gaze metric analysis by moment

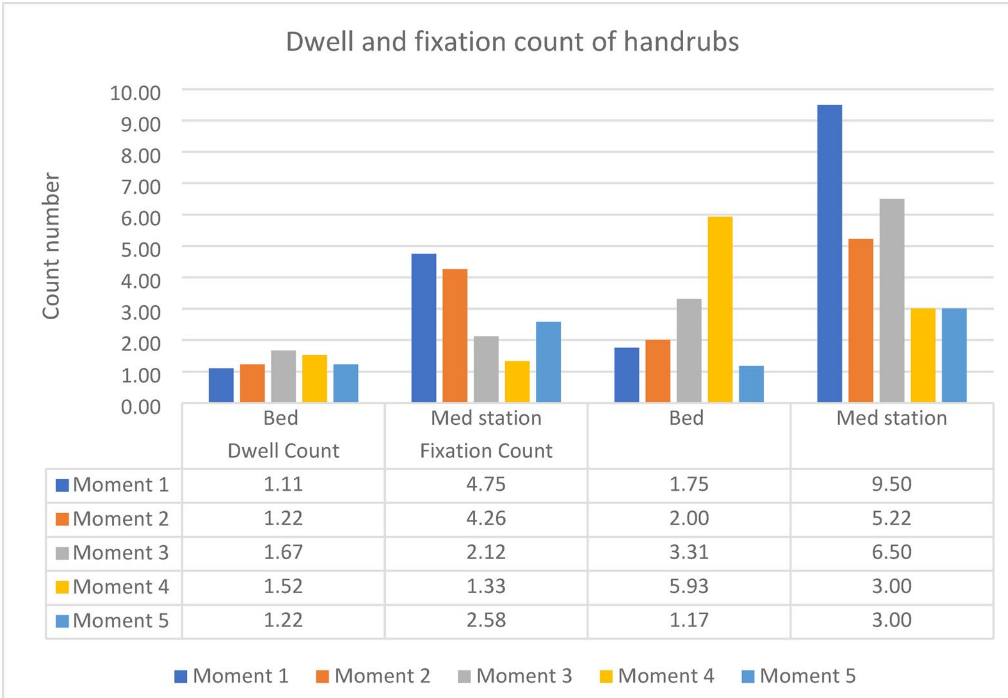
The analysis of visual attention patterns examined both gaze-based and fixation-based metrics for each hand hygiene moment. Gaze-based metrics incorporated all eye movements, comprising both fixations (intervals when the eyes remain fixed and concentrated) and saccades (rapid shifts between fixation points), quantifying the cumulative visual engagement with each AOI. In contrast, fixation-based metrics specifically evaluated instances of sustained visual attention, indicating conscious recognition and cognitive processing of the AOIs within the clinical environment.

Results demonstrated distinct patterns of visual attention toward the two ABHR locations—one positioned near the patient's bed and another at the medical station (Figs. 3 and 4). Across all moments, the medical station

Table 4 Hand hygiene compliance rate of HCWs

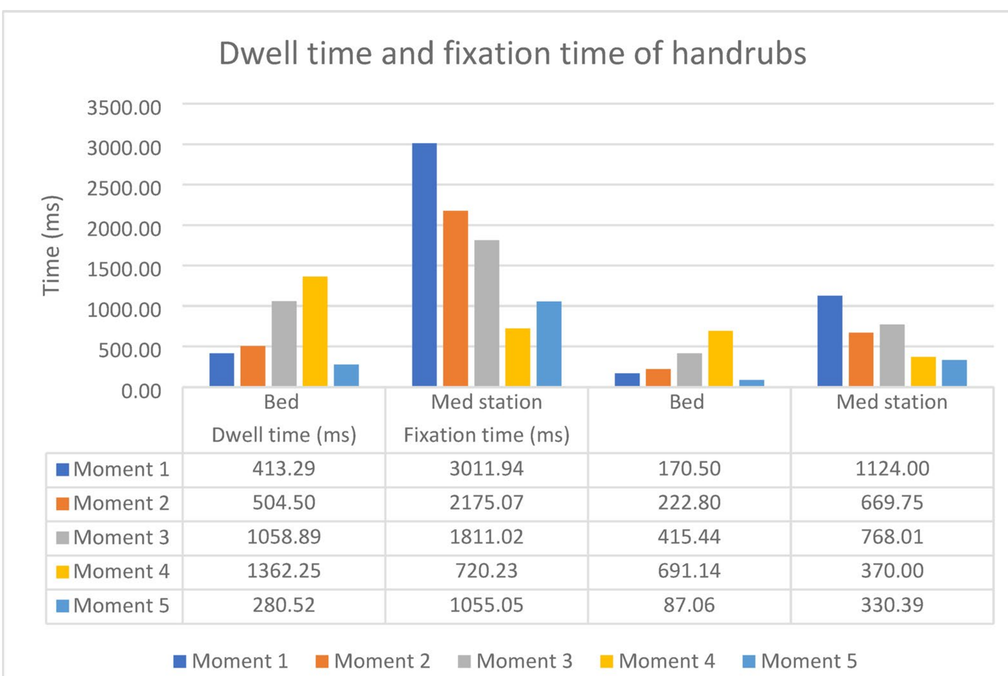
Characteristics	Compliance rate (%)						*P*-value	Individual with compliance rate ≥ 75%	
	BP	AP	BA	ABF	APS	Total		≥ 75%	
Hospital							0.107		0.060
Hospital I (n = 39)	40.4%	82.4%	48.7%	64.1%	55.3%	56.9%		14 (35.9%)	
Hospital II (n = 36)	21.6%	54.8%	50.0%	52.8%	36.1%	42.6%		6 (16.7%)	
Position							0.930		0.341[a]
Doctor (n = 16)	43.8%	71.4%	37.5%	68.9%	43.8%	52.6%		6 (37.5%)	
Nurse (n = 59)	29.4%	68.6%	52.5%	55.9%	46.6%	49.5%		14 (23.7%)	
Working experience							0.872		0.778
≤ five years (n = 32)	37.8%	74.1%	43.8%	53.1%	45.2%	49.7%		8 (25.0%)	
> five years (n = 43)	27.7%	65.8%	53.5%	62.8%	46.5%	50.5%		12 (27.9%)	
Age group							0.075		0.011[a]*
< 35 years' old (n = 58)	29.2%	66.0%	48.3%	53.4%	36.8%	45.8%		11 (19.0%)	
≥ 35 years' old (n = 17)	42,1%	80.0%	52.9%	76.5%	76.5%	64.7%		9 (52.9%)	
Gender							0.666		1.000[a]
Male (n = 17)	31.3%	53.8%	52.9%	64.7%	35.3%	47.5%		4 (23.5%)	
Female (n = 58)	32.4%	73.1%	48.3%	56.9%	49.1%	50.9%		16 (27.6%)	

**P*-value < 0.05. [a]*P* value obtained using Fisher's exact test



	Bed Dwell Count	Med station	Bed Fixation Count	Med station
Moment 1	1.11	4.75	1.75	9.50
Moment 2	1.22	4.26	2.00	5.22
Moment 3	1.67	2.12	3.31	6.50
Moment 4	1.52	1.33	5.93	3.00
Moment 5	1.22	2.58	1.17	3.00

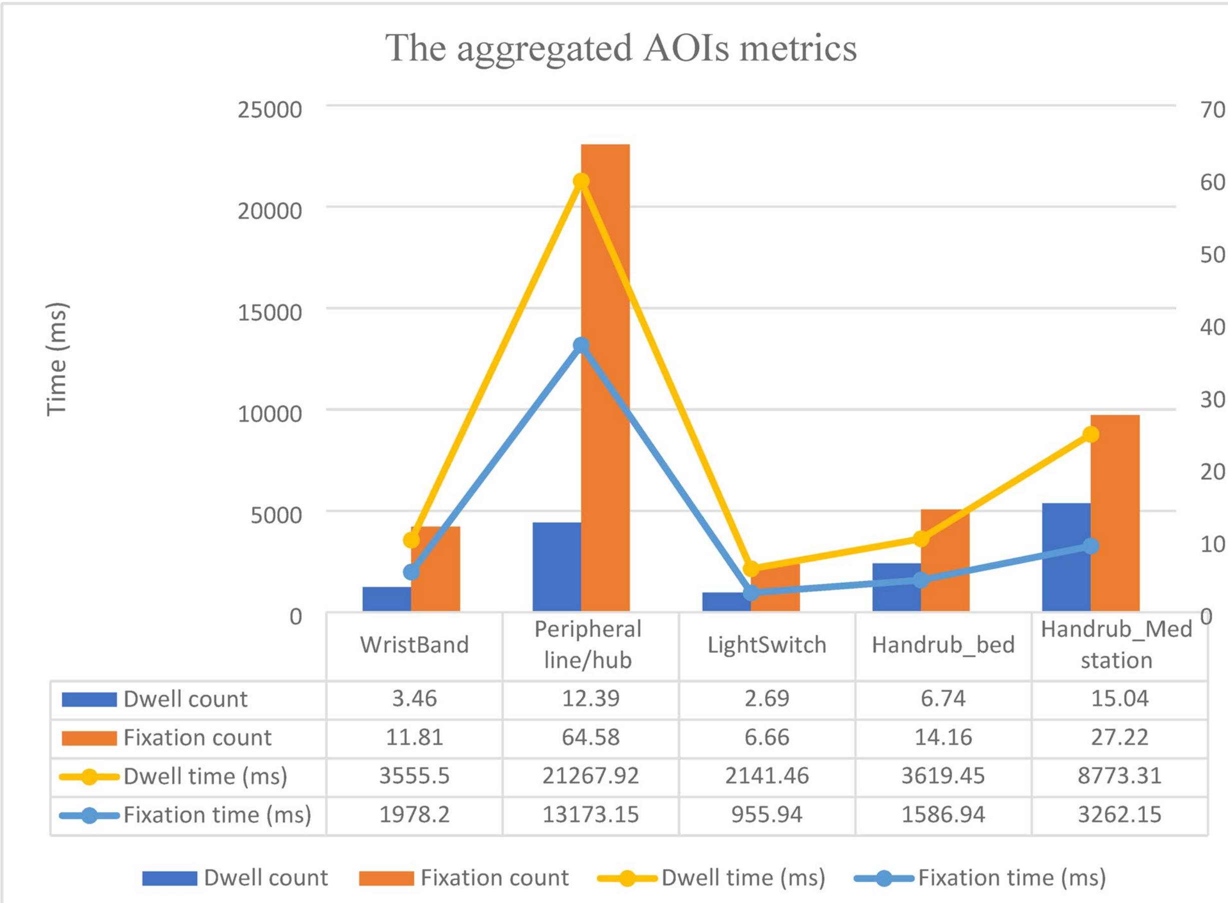
Fig. 3 Visual attention on handrub action



	Bed Dwell time (ms)	Med station	Bed Fixation time (ms)	Med station
Moment 1	413.29	3011.94	170.50	1124.00
Moment 2	504.50	2175.07	222.80	669.75
Moment 3	1058.89	1811.02	415.44	768.01
Moment 4	1362.25	720.23	691.14	370.00
Moment 5	280.52	1055.05	87.06	330.39

Fig. 4 The dwell and fixation time of handrubs

dispenser attracted significantly greater visual engagement, with higher mean values for dwell count (15.04), fixation count (27.22), and saccades (106.95). Notably, during Moment 1 (before patient contact), the medical station ABHR showed peak visual attention metrics (dwell: 4.75; fixation: 9.50; saccades: 35.86). However, an exception occurred during Moment 4 (after patient contact), where the bedside dispenser received marginally greater fixation count (5.93) and dwell count (1.52), along with substantially longer dwell duration (1362.25 ms) and



	WristBand	Peripheral line/hub	LightSwitch	Handrub_bed	Handrub_Med station
Dwell count	3.46	12.39	2.69	6.74	15.04
Fixation count	11.81	64.58	6.66	14.16	27.22
Dwell time (ms)	3555.5	21267.92	2141.46	3619.45	8773.31
Fixation time (ms)	1978.2	13173.15	955.94	1586.94	3262.15

Fig. 5 The aggregated AOIs metrics

fixation time (691.14 ms). Dominant visual attention at medical stations suggests that the HCWs are more visually oriented to use ABHR when located at centralized medical stations likely due to the workflow and ease of access of the ABHR.

The analysis of visual attention patterns extended beyond handrub dispensers to include other clinically relevant AOIs, with results presented in Fig. 5. The data revealed distinct patterns of visual engagement across different AOIs, including wristbands, peripheral line/hub connections during scrub-the-hub procedures, and light switches. Notably, the peripheral line/hub connection during scrub-the-hub protocols received greater visual attention than other AOIs, demonstrating both prolonged dwell time and extended fixation duration.

Discussion

This study found an overall hand hygiene compliance rate of 50.1% across two teaching hospitals in Malaysia, with only 20 out of 75 HCWs achieving the compliance threshold of over 75%. These results differ with Malaysia's 2022 national average of 85% as reported in the Infection Prevention & Control and Antimicrobial Resistance Containment Program Annual Report [17]. The higher compliance rate observed at the national level maybe attributed to the Hawthorne effect, as routine audits involve visible observation. However, the small sample size and controlled experimental conditions of our study may not fully reflect the broader clinical practice measured in the national surveillance data.

The lack of significant differences in compliance rates between the two hospitals suggests that factors like year of establishment or IPC program duration may have less impact than elements such as workload, staffing, attitudes and safety culture.

Compliance rates also varied significantly across different moments, with the lowest adherence observed before patient contact and the highest after patient contact. The pattern aligns with existing literature suggesting that HCWs demonstrate greater compliance when perceiving self-protection needs (after patient contact) as compared to protecting patients (before patient contact) [18]. The observed compliance disparity suggests HCWs perceiving lower microbial contamination risk prior to patient contact compared to the visibly apparent contamination after patient contact [18]. Studies suggested poor hand hygiene is largely due to behavior issues and recommended programs to correct HCWs' behavior are important to improve hand hygiene compliance [19, 20].

In this study, the average handrub duration across both hospitals was only 13.63 s, significantly shorter than the WHO-recommended 20–30 s standard [13]. Hospital-specific data showed averages of 10.72 s in Hospital I and just 7.96 s in Hospital II, indicating a widespread failure to meet evidence-based guidelines. Similarly, scrub-the-hub durations (7.6 s in Hospital I; 4.13 s in Hospital II) failed to meet the 10–15 s recommendation by The Joint Commission. These findings are particularly alarming given the well-established relationship between proper technique duration and microbial reduction [21], especially for high-risk procedures involving central venous catheters, which are well-known as a source of infection [22]. Based on the observed durations, this finding suggests that current practices may be compromising patient safety and increasing the risk of HAIs.

Traditional hand hygiene audits using direct observation remain the gold standard for monitoring HCWs' compliance with the WHO "5 Moments for Hand Hygiene". However, this method has several well-documented limitations, including time-intensive, potential observer bias, and lack of standardization in practice [23]. Additionally, conventional audits typically capture only brief snapshots of clinical workflows, potentially missing important behavioral patterns and scrubbing duration [24].

Technological advances have introduced electronic monitoring systems that address some limitations of manual audits. These systems fall into three main categories, which are application-assisted, camera-assisted, and sensor-assisted methods [25]. Digital handrub monitoring systems, for instance, provide automated tracking of sanitizer usage frequency and patterns [26, 27]. These electronic solutions offer real-time data collection and reduced observer bias [25]. However, they cannot assess the quality or technique of hand hygiene practices.

This study employed eye-tracking technology to overcome these limitations, providing objective behavioral data through visual attention metrics. The approach offers several advantages over traditional methods. Firstly, hand hygiene audits with eye-tracking technology offers better data quality and reliability. Eye-tracking captures comprehensive visual behavior data, minimizing the Hawthorne effect and observer bias inherent in manual audits [12]. The recorded sessions also allow for retrospective analysis and verification. Besides compliance rates, the technology measures detailed parameters including handrub duration, scrub-the-hub duration and visual attention pattern such as dwell times, fixation counts and saccade metrics.

Eye-tracking technology also provided detailed gaze metrics and parameters, including dwell time, dwell count, fixation time, fixation count and saccade metrics, offering valuable insights into HCWs' preferences and behaviors and contributing to a deeper understanding of hand hygiene compliance dynamics. The results revealed that ABHR at medical stations received more visual attention than the one near patient beds, as evidenced by fixation patterns. Increased fixation counts within an AOIs suggest that an element was more noticeable, useful or important [28]. HCWs were more likely to engage with ABHR dispensers at medical stations, but higher attention to bedside ABHR at moment 4 (after touching the patient), likely due to better visibility and workflow integration. This is supported by a study that reported that the accessibility of ABHR dispensers is a critical factor in hand hygiene compliance [29]. Hence, the differential attention patterns exhibited from these findings may reflect workflow considerations, with HCWs more likely to consciously look at the bedside dispenser after completing direct patient care activities, while routinely noticing the medical station dispenser during general clinical tasks.

Interestingly, while HCWs frequently noticed the medical station dispensers, this visual attention did not consistently translate into compliance, particularly for Moment 1 (before patient contact). Higher fixation times and saccade counts for ABHR dispensers at the medical station indicate that HCWs have noticed these dispensers and are processing the information. Longer fixation durations often signify extended information processing, while higher saccade counts reflect more time spent searching for relevant elements [28]. However, the low compliance rate for moment 1 suggests that while HCWs were aware of the dispensers, they did not consistently perform the hand hygiene task.

The technology also highlighted the cognitive demands of complex procedures like peripheral line maintenance, which required the most sustained visual attention. Peripheral line and hub during scrub-the-hub process showed the highest dwell time and fixation duration, indicating frequent rechecking gaze and reflecting the complexity of this AOI. The extended visual engagement may be due to the heightened attention required during the scrubbing process.

These findings have several important implications for improving hand hygiene compliance in clinical settings. First, they underscore the need for targeted interventions addressing both the quality and duration of hand hygiene practices, moving beyond simple compliance counting to ensure proper technique execution. Second, the visual attention patterns suggest opportunities for environmental modifications, such as strategic repositioning of dispensers to better align with HCWs natural sight lines and workflow patterns. Educational interventions and nudging strategies near critical areas, such as the bedside, could encourage better compliance for certain hand hygiene moments. More importantly, enhancing visibility, proximity, and accessibility of bedside dispensers can potentially align the HCWs' behavior with the 5 Moments more effectively. Third, the study demonstrates the value of incorporating advanced technologies like eye-tracking into compliance monitoring, as these tools can reveal objective behavioral insights that traditional observation methods might miss. This includes the potential use of eye trackers for personalised feedback and alerts during hand hygiene audit training among HCWs, and for redesigning dispenser placements in the hospital environment. One notable benefit of using eye-tracking is that it allows participants to carry out their usual healthcare tasks naturally, without direct interference or observation, thereby reducing potential observer-related biases compared to conventional study designs.

Although eye-tracking technology offer valuable behavioural insights into hand hygiene performance, several limitations on its practical application should be acknowledged. The cost of hardware and software (e.g., Pupil Labs and iMotions) may limit scalability in resource-constrained settings. Data processing and video annotation require technical expertise, which may restrict the hospital implementation. In addition, incompatibility with spectacle wearers may reduce inclusivity. Although study on eye-tracking for monitoring hand hygiene of HCWs have been reported, the technology has yet to be validated for routine IPC audits in healthcare systems. This study was conducted in stimulated clinical setting, limited to two hospitals with modest sample size (n = 75), which may restrict the generalisability of the findings and may not fully capture the complexity of real-world environment. Therefore, while the method has strong research utility, further validation, testing in real-world settings, and cost–benefit evaluation are required before it can be considered for operational use in infection prevention programs.

Conclusion

This study demonstrates how eye-tracking technology provides unique behavioral insights that complement traditional audit methods. The technology revealed both quantitative gaps in practice duration and qualitative patterns in visual attention that influence compliance. For example, eye-tracking data revealed that the average handrub and scrub-the-hub duration in both hospitals was below the recommended standard. This has been recognized as an often-overlooked factor that could potentially increase the risk of HAIs. A multifaceted approach addressing individual behavior, environmental design, and monitoring systems appears most promising for sustainable practice improvement. Future research should investigate longitudinal interventions combining these elements to assess their impact on both compliance metrics and clinical outcomes towards refining infection control standards and protocols.

Acknowledgements
We thank the University of Malaya, Universiti Malaya Medical Centre, Hospital Sultan Abdul Aziz Shah for its support and facilities. Special thanks to infection control nurses from UMMC and HSAAS—Siti Shuhaida Samsudin, Haryani Che Hamzah, Siti Norintan Zainon, Noor Adirah Zarif, Nor Hasidah Ismail, Siti Hamidah Shamsuddin, Siti Sakinah Mohd Sidik, Norlaila Sallehhudin, and Nursyahirah Mohd Khair for their help in participants recruitment, design of hand hygiene scenario, hand hygiene assessment and arrangement of the stimulated ward

Author contributions
Conceptualization: UHO, SP, CSJT; Methodology: MYL, UHO, CSJT; Formal analysis and investigation: MYL, CWC; Writing—original draft preparation: MYL; Writing—review and editing: CWC, SP, UHO, CSJT; Funding acquisition: CWC, TZMTJ, UHO, CSJT; Resources: SP, TZMTJ, CSJT; Supervision: SP, UHO, CSJT; Data curation: CWC; Validation: UHO; Visualisation: MYL, NAS, UHO; Project administration: CSJT; Software: CWC. All authors read and approved the final manuscript.

Funding
This research was funded by the Transdisciplinary Research Grant Scheme (TRGS) (TRGS/1/2020/UM/02/2/2), grant number TR001B-2020 and MRUN Young Researchers Grant Scheme, grant number MR002-2019.

Data availability
The data that support the findings of this study are not openly available to protect participants privacy and are available from the corresponding author upon reasonable request.

Declarations

Ethics approval
This study was approved by the University of Malaya Medical Centre (UMMC) Medical Research Ethics Committee (MREC No: 2020117-8191) and Ethics Committee for Research involving Human Subjects of University Putra Malaysia (JKEUPM-2020-313).

Informed consent
Informed consent was obtained from all individual participants included in the study.

Competing interests
The authors declare no competing interests.

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Received: 5 July 2025 / Accepted: 28 November 2025
Published online: 27 January 2026

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