Journal Pre-proof

The use of Smart Environments and Robots for Infection Prevention Control: a systematic literature review.

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PII: S0196-6553(23)00109-8
DOI: https://doi.org/10.1016/j.ajic.2023.03.005
Reference: YMIC 6472

To appear in: *AJIC: American Journal of Infection Control*

Please cite this article as: Davide Piaggio , Marianna Zarro , Silvio Pagliara , Martina Andellini , Abdulaziz Almuhini , Alessia Maccaro , Leandro Pecchia , The use of Smart Environments and Robots for Infection Prevention Control: a systematic literature review., *AJIC: American Journal of Infection Control* (2023), doi: https://doi.org/10.1016/j.ajic.2023.03.005

Highlights

- IPC strategies innovation is key to improve pandemic preparedness and response.
- Current hospital IPC practices do not rely on automation and robotic technology.
- High need to raise the awareness of IPC practitioners on such technologies.
- High need to implement contextualized alternatives for lower income countries.

The use of Smart Environments and Robots for Infection Prevention Control: a systematic literature review.

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Abstract

Infection prevention and control (IPC) is essential to prevent nosocomial infections. The implementation of automation technologies can aid outbreak response.

This manuscript aims at investigating the current use and role of robots and smart environments on IPC systems in nosocomial settings.

The systematic literature review was performed following the PRISMA statement. Literature was searched for articles published in the period January 2016 to October 2022. Two authors determined the eligibility of the papers, with conflicting decisions being mitigated by a third. Relevant data was then extracted using an ad-hoc extraction table to facilitate the analysis and narrative synthesis. The quality of the included studies was appraised by two authors.

The search strategy returned 1520 citations and 17 papers were included in this review. This review identified three main areas of interest: hand hygiene and personal protective equipment compliance, automatic infection cluster detection and environments cleaning (i.e., air quality control, sterilization).

This review demonstrates that IPC practices within hospitals mostly do not rely on automation and robotic technology, and few advancements have been made in this field. Increasing the awareness of health care workers on these technologies, through training and involving them in the design process, is essential to accomplish the Health 4.0 transformation. Research priorities should also be considering how to implement similar or more contextualized alternatives for low-income countries.

Keywords

Infection prevention and control; robot; artificial intelligence; internet of things; hand hygiene; health 4.0

Introduction

At the end of 2019, anomalous pneumonia cases were identified in Wuhan City (China) and were reported to the World Health Organization (WHO) on 31 December 2019. Scientists were able to identify the cause of these atypical pneumonia cases: a new strain of coronavirus, later renamed as SARS-CoV-2. From then on, the situation rapidly degenerated until when, a few months later, the WHO declared the disease caused by SARS-CoV-2 (COVID-19) a global pandemic. As of 25 October 2022, there have been 625 million confirmed cases of COVID-19 globally, and 6.5 million deaths have been reported by the WHO.

The geographic distribution of COVID-19 cases is uneven, with Europe still being the most affected WHO Region (totaling 260 million of confirmed cases, against the nine million confirmed cases in the Africa WHO Region) [1]. Multiple attempts to explain these differences have been made, i.e., genetic immunity, climatic conditions, population' age, different screening activities [2], as well as undertesting and underreporting [3, 4]. One thing is certain, higher resource settings found themselves, for the first time after World War II, in conditions of deprived resources, typical of lower resource settings (e.g., scarcity of ventilators, personal protective equipment (PPE), beds in hospitals, health care workers, etc.) [5].

One of the key lessons learned from COVID-19 was the extreme urgence to better prepare for future pandemics, with prevention and containment measures enlisted as top priorities of both political leaders and scientists. Certain circumstances, such as the climate crisis and the growing global population, will, in fact, likely lead to new pandemics, due to the increased risk of zoonoses. These reasons reinforce the interest of the scientific community in developing new and more efficient solutions to such threats. This paper will help showcase new approaches developed and tested for infection prevention and control (IPC) purposes in particular in the field of robotics and automation, and hopefully will help improve hospital responses and preparedness to forthcoming outbreaks.

Various studies [6, 7] highlighted the weaknesses of IPC guidelines, which did not ensure an effective response to the COVID-19 pandemic. In 2022, in hindsight, the Lancet Commission highlighted the key components needed for effective preparedness plans, one of which is the prompt adoption of IPC procedures designed following the most updated knowledge on transmission routes of respiratory infectious diseases [7]. On the other hand, the WHO published a statement in response to the Lancet Commission, chronologically showing that their approach during the first waves of COVID-19 was as adequate and efficient as possible [8]. Therefore, prompt innovation of IPC strategies remains crucial to improve preparedness and healthcare response to pandemics. In fact, IPC was also pinpointed as a research priority by the Global Research Forum, organized by the WHO, at the start of the pandemic, in February 2020. After almost two years' worth of work, which saw the joint effort and collaboration of international experts with different backgrounds, in December 2021, the WHO published the document "Infection prevention and control in the context of coronavirus disease (COVID-19): A living guideline", replacing an old version dating back to December 2020. The most recent version was last updated on April 2022, mostly revising the advice on mask use for children, thanks to the United Nations Children's Fund (UNICEF) contribution [9].

Technological innovation is playing a leading role in the "new approach" of Health 4.0 and certainly offers promising solutions for hospital responses to future epidemic/pandemic outbreaks. The shift in healthcare driven by Health 4.0 is based on the integration of Internet of Things, Cloud and Fog Computing, and Big Data [10]. It is clear that automation, digital tools and robots could have played a key role in the IPC in healthcare settings, and they should therefore be leveraged to ensure more crucial roles in this remit. ODIN, one of the biggest trailblazing Horizon 2020 projects in the field of robotics applied to healthcare, is already looking into this direction, aiming to enhance hospital safety, productivity and quality relying on artificial-intelligence-based technologies [11].

The purpose of this paper was to conduct a systematic literature review on the use of robots and automation for IPC purposes in healthcare settings, focusing on nosocomial infections. We intended to investigate the performance measures, the healthcare workers (HCWs) compliance, as well as cost and resources needed (including personnel, time, infrastructure, existing servers/computer systems, etc) of IPC technologies compared with the gold standard of practice, if existent. This is of vital importance for informing the preparedness plans to tackle the next global health emergency.

Methods

The methodology that was applied followed the PRISMA statement for systematic literature reviews [12].

Search strategy

In order to carry out the systematic literature review, significant keywords were selected and included in a search string. Such keywords were identified by reading relevant infection prevention and control (IPC) literature, in particular the World Health Organization (WHO) Guidelines for Infection prevention and control guidance for long-term care facilities in the context of COVID-19 [13]. These were then reviewed and discussed by the Applied Biomedical Signal Processing and Intelligent eHealth (ABSPIeH) lab members, composed of biomedical engineers, computer scientists, biologists, and bioethics experts. . These terms, which were combined using Boolean operators (e.g., AND, OR), are hereby reported: “Infection prevention and control”, “Infection prevention and control program”, “infection prevention”, “infection control”, “transmission control”, “health care”, “assistive care”, “hospital”, “robot”, “telerobotic”, “teleoperation”, “automated technology”, “artificial intelligence”, “machine learning”, “deep learning”, “internet of things”, “smart device”, “smart service”, “smart technology”, “sensor”, “wearable”, “key enabling technology”, “human support robot”. The full search string can be found in Supplementary Figure A1. This search was performed on OVIDSp for the period January 2016 to October 2022. This was originally searched in 2021 limiting the search to the previous 5 years. The search was then expanded in a second stage by looking for all the contributions between March 2021 and October 2022.

Inclusion/exclusion criteria.

We judged eligible peer reviewed journal articles, written in English, that reported on automation technologies for Infection Prevention and Control (IPC) in health care settings. Letters to editors, book chapters, editorials and notes were excluded. Reviews were also excluded, and they were only screened to check if there were any recent ones analogous to our review. No recent review dealt with the same topic. Moreover, articles that dealt with patients' screening, diagnosis and other procedures not relevant to IPC were excluded. The articles were appraised by two authors by title, abstract, and, finally, full text, while a third one independently reviewed the results of the screening. Disagreements among the two authors were solved by arbitration of the third.

Data extraction and quality appraisal.

Relevant data was extracted and collected in an ad-hoc Excel sheet (see Supplementary Table A1). The extracted data was organized by five macro areas, i.e., broad thematic areas: (1) hand hygiene compliance, (2) cleaning and disinfection of hospital environment, (3) infection cluster detection, (4) air quality control, (5) correct use of PPE. The quality appraisal was conducted using the MMAT tool [14], due to the mixed types of studies considered. The MMAT tool contains different subsections that allow for the assessment of both quantitative and qualitative studies.

Data synthesis.

To synthesize the data extracted and collected we used the narrative synthesis method [15, 16]. For each paper we identified the focus of interest, which was then described in the result section and organized based on principal themes (i.e., interpretive approach). This information is then used to formulate discussions and possible solutions [16].

Results

Search outcome

The OvidSP search and study selection process is summarized in Figure 1. The aforementioned combined searches returned 1520 hits, 21 of which were duplicates from the previous search; thus, they were excluded. Overall, 17 articles met our inclusion criteria (Supplementary Table A2 reports the reasons for exclusions for the full text screening round).

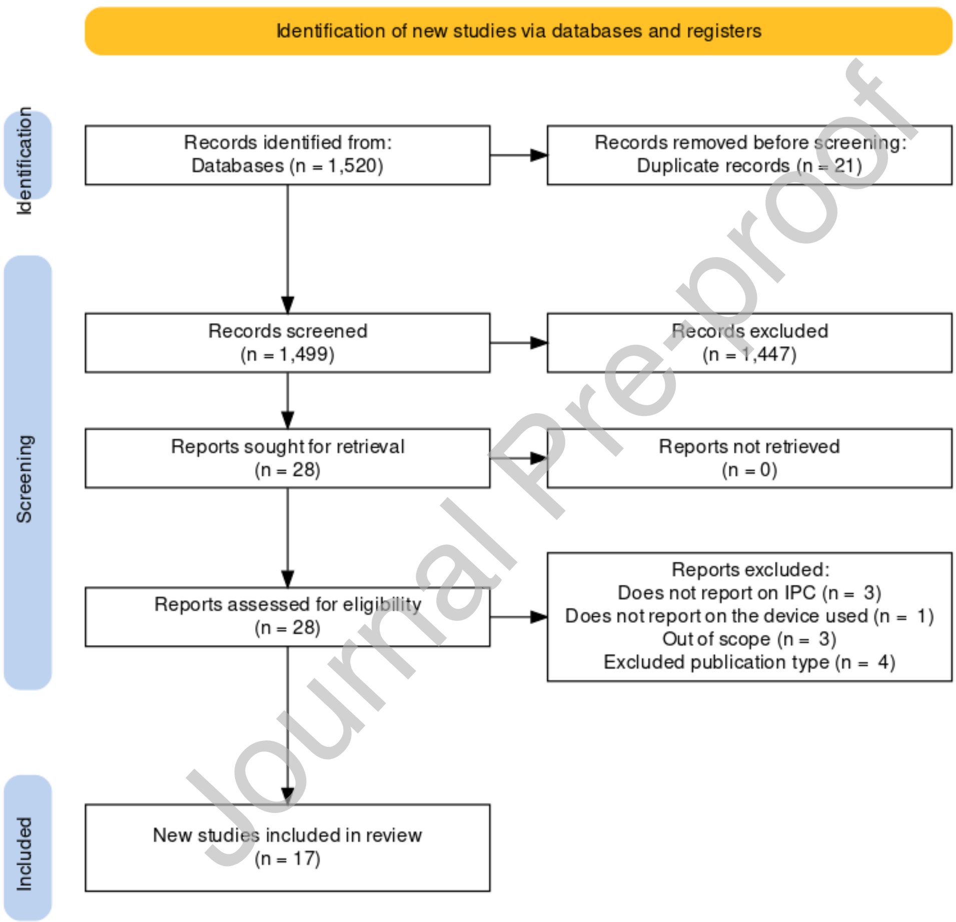

Figure 1. PRISMA flow diagram. Study selection process used, divided into three phases: identification, screening, included.

Data extraction

Table I summarizes the essential information, including the IPC device used, the aim of the study, macro area, the participants for each study and hospital department.

Table I. Study characteristics.

Study	Macro area	IPC device	One-sentence aim of the study	Participants	Hospital department/area
Xu N 2021[17]	Hand hygiene compliance	IOT hand hygiene compliance monitoring device	Evaluation of IPC device impact on hand hygiene (HH) compliance and healthcare-associated infection rates	Hospital staff (54): specialized doctors, doctors, nurses, and cleaners Patients (697)	Electronic Intensive Care Unit (EICU)
McCalla S 2017[18]	Hand hygiene compliance	Hand hygiene compliance system - Biovigil Healthcare Systems Inc, Ann Arbor, MI	Evaluation of IPC device impact on HH compliance	Hospital staff: nurses, nurse technicians, respiratory therapist, care managers, dietary aides, housekeeping staff Patients (4070)	Intensive Care Unit (ICU)
McCalla 2018[19]	Hand hygiene compliance	Hand hygiene compliance system - Biovigil Healthcare Systems Inc, Ann Arbor, MI	Evaluation of IPC device impact on healthcare-associated infection rates	Hospital staff: nurses, nurse technicians, respiratory therapist, care managers, dietary aides, housekeeping staff Patients (36,890)	Whole hospital
Edmisten C 2017[20]	Hand hygiene compliance	Electronic HH monitoring system, based on radiofrequency	Report on IPC device implementation, challenges, and success	Hospital staff (2830)	Three comunity hospitals
Dufour JC 2017[21]	Hand hygiene compliance	Electronic HH monitoring system, based on radiofrequency	Report on HH compliance	Hospital staff (42): 23 medical doctors, eight residents, 12 medical students, three senior	Seven patient rooms, unit not specified

Study	Macro area	IPC device	One-sentence aim of the study	Participants	Hospital department/area
				doctors, six nurses, nine assistant nurses and four housekeepers	
Iversen AM 2020[22]	Hand hygiene compliance	HHC automated monitoring system (Sani nudge)	Evaluation of HH compliance	Hospital staff: 42 nurses	Orthopedic surgery department, oncology department
Xu Q 2021[23]	Hand hygiene compliance	Electronic HH system - Sanibit	Validation of IPC device	Hospital staff (15): 12 nurses, two patient care assistants and one secretary	Surgical intensive care unit
Xu Q 2022[24]	Hand hygiene compliance	Electronic HH system - Sanibit	Evaluation of HH individual behaviors	Hospital staff (15): 12 nurses, two patient care assistants and one secretary	Surgical intensive care unit
Akkoc G 2021[25]	Hand hygiene compliance	Electronic hand hygiene reminding and recording systems (EHHRRSs)	Validation of IPC device	Hospital staff: nurses, physicians, transporters, and other staff Patients (248)	Anesthesia and reanimation intensive care unit
Huang F 2021[26]	Hand hygiene compliance	automatic hand hygiene monitoring system (MediHandTrace), based on radiofrequency	Evaluation of IPC device impact on HH compliance	Hospital staff: 38 physicians, 13 interns, 37 nurses, 18 nursing assistants, and five housekeeping personnel	Infection unit
Durant DJ 2020[27]	Hand hygiene compliance	Electronic hand hygiene monitoring systems (EHHMS)	Report on New York State hospitals' adoption of EHHMS. Evaluation of IPC device on C. Difficile infection rates	56 hospitals	Not relevant

Study	Macro area	IPC device	One-sentence aim of the study	Participants	Hospital department/area
Stachel A 2017[28]	Infection cluster detection	Statistical software SaTScan and software for laboratory data management WHONET	Report on IPC device implementation	Patients	Two hospitals
Aghdassi SJS 2021[29]	Infection cluster detection	automated cluster alert system (CLAR)	Report on IPC device implementation and on cluster detected	Patients	Whole hospital
Colella Y 2022[30]	Air quality control	Operating room air quality monitoring system based on fuzzy logic (FL)	Report on IPC device development	Hospital staff, Patients	Operating room (OR)
Preda VA 2022[31]	Correct use of PPE	Artificial intelligence-personal protective equipment (AI-PPE) compliance system	Validation of IPC device	Hospital staff (74): six nurses, 14 medical students, three physicians, nine junior medical officer, three surgeons, 31 laboratory staff and eight administrative staff	Not specified
Wang Y 2022[32]	Cleaning and disinfection of hospital environments	RNN neural networks with the addition of PDCA cycle related element	Evaluation of IPC device impact on workers' satisfaction and standardization rates	Hospital staff: 17 room nurses	Supply room
Khan ZH 2020[33]	Cleaning and disinfection of hospital environments	Different types of robotic technologies are used in hospital setting to dry vacuum and mopping to remove germs and pesticides. - intelligent navigating vacuum pump - ultra-violet radiation based device - highly dynamic	Report on robot utilization to menage the COVID-19 pandemic	Not relevant	Not relevant

Study	Macro area	IPC device	One-sentence aim of the study	Participants	Hospital department/area
		robotic gripper and sensing system - autonomous heavy-duty cleaning robot			

Out of the 17 included studies, 11 focused on hand hygiene (HH) compliance of HCWs [17-27], two reported on automatic cluster detection systems [28, 29]. Four articles addressed different streams, namely air quality control [30], personal protective equipment (PPE) compliance [31], and hospital spaces' cleaning and disinfection [32, 33]. An overview of the technologies presented in the included studies is shown in Figure 2.

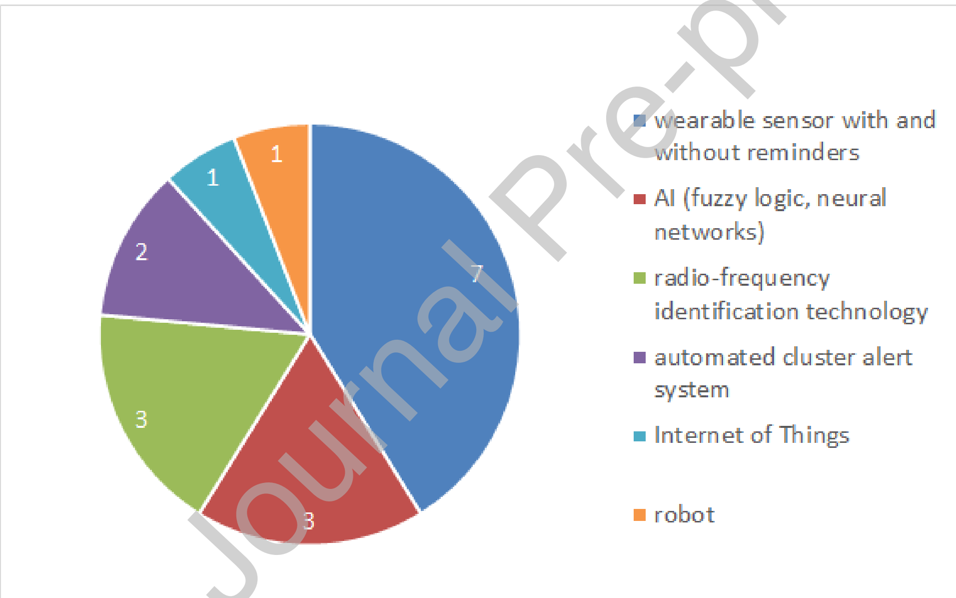

Figure 2. Technologies employed by the studies included: wearable sensor with and without reminders (7), artificial intelligence (AI) (fuzzy logic, neural networks) (3), radio-frequency identification technology (3), automated cluster alert system (2), Internet of Things (1), robot (1).

The rest of this section will summarize and group the results by the aforementioned five macro areas.

Hand hygiene compliance.

As previously stated, most of the studies investigated the use of automated technologies for monitoring and encouraging hand hygiene compliance of HCWs. Eight of these studies tackled the problem using wearable sensors, with some of them including signaling devices that reminded HCWs to complete the task of sanitizing their hands [17-19, 22-25, 27].

McCalla et al. developed an automated hand hygiene compliance system (HHCS), based on sound and light signals activated when a HH opportunity is detected. In their first article (2017) they assessed the effects of HHCS on HCWs' hand hygiene in the intensive care unit, comparing it to the gold standard, i.e., human observation [18]. They found that, despite a higher number of HH opportunities recorded, there was a lower number of actual HH events. In 2018, they implemented and pilot tested the same system in the whole hospital [19]. In this case, they observed a significant reduction in the rate of catheter-associated urinary tract infections and of central line-associated bloodstream infections. In both studies the Biovigil system (Biovigil Healthcare Systems, Inc, Ann Arbor, MI) was used. This system is the only electronic hand hygiene monitoring solution that provides a reminder to sanitise hands, reassuring patients and anybody else at the bedside that hand hygiene has been performed.

Similarly, Xu N. et al. used an Internet of Things HH monitoring device during the study period. To monitor the process, they installed five transmitters connected to an IoT gateway wirelessly. In contrast with McCalla et al., they observed a drastic increase of HH compliance rate. However, the infection rates of the hospital were not significantly different [17]. Xu Q. et al. adopted the Sanibit system to assess HH compliance and behaviors among HCWs in the surgical intensive care unit. The Sanibit system works thanks to room sensors and Bluetooth wristbands, which detect HH opportunities and monitor HH compliance and quality. The system is enhanced by real-time feedback via the wristbands, a gamification app where each HCW can check their performance, and an automated HH compliance analysis. In 2021, they published the results of the validation of the technology and they also reported a significant difference between individual HCWs' HH behaviors [23]. In 2022, they published the results of an expansion of these observations using the same systems and participants. In this case, they report higher compliance rates when exiting the patient room and after long visits compared to the compliance rate when entering the patient room or after short visits [24]. The differences in individual HH behavior patterns suggest that personalized interventions could improve HH compliance.

Similar to the work of McCalla et al., Akkoc et al. found a significant reduction of healthcare-related infections, specifically central line-associated bloodstream infections and a ventilator-associated pneumonia, when considering the effects of tools to raise HH awareness. In particular, they analyzed the effect of an electronic HH recording and reminder system (EHHRRSs) on nosocomial infection rates, comparing it to the conventional observation method [25]. The authors also point out that the discontent of HCWs regarding the use of the tracking device limited the duration of the study.

Regarding the adoption of such tools, Durant et al. found, through surveys and interviews, that the number of hospitals adopting an Electronic HH Monitoring System (EHHMS) in the New York State area was low, mostly due to cost and concerns on the accuracy of the devices [27]. Moreover, their analysis on the EHHMS' impact on hospital-acquired Clostridium difficile shows no significant effect. The sanitizers' location was proved to be key to HH compliance by Iversen et al., using an automated monitoring system to evaluate HH compliance. They also could not find any association between HH compliance and the number of beds in rooms [22].

A different approach was adopted by three of the 11 articles dealing with HH compliance, using devices based on radio-frequency identification (RFID) technologies [20, 21, 26]. This is the case for the system reported by Dufour et al., called 'MedihandTrace' (MHT), which meets most of the WHO requirements for an automated hand hygiene systems: continuous recording of HCWs paths and of HH opportunities, addressing the Hawthorne effect (i.e. the behavior changes when the subject is observed), implementing real-time remainders, and decreasing time and technical expertise needed [21]. Huang et al. used the same system to assess the impact of real-time reminders on HH compliance [26]. They reported an increase of the overall compliance, and they proposed the use of randomized reminders to reduce alarm fatigue of the HCWs. Lastly, Edmisten et al. implemented a similar technology in three community hospitals, and informally observed facility-wide decrease in hospital-acquired infections [20].

Cleaning and disinfection of hospital environments.

Another IPC process reported in the macro areas is the cleaning and disinfection of hospital environments [32]. Wang et al. reported on the application of Plan-Do-Check-Act (PDCA) cycle based on artificial intelligence (AI) algorithms in the management of the sterilization of supply rooms. Mainly, they rely on several Long Short-Term Memory (LSTM) neural networks units using three types of gating: input gates, forgetting gates, and output gates. LSTMs store and update information through the gating, which works as a fully connected layer. They observed a significant increase in the satisfaction rates and compliance with standardized practices in the group using the PDCA cycle compared to the group using the conventional management method.

Moreover, Khan et al. researched the use of robots in hospital settings during COVID-19 pandemic [33]. We focused our attention on the cleaning robots. The paper describes the use and application of different types of cleaning robotic technologies in hospital settings, relying on dry vacuum and mopping to remove germs and pesticides. Other examples of technologies include intelligent navigating vacuum pump, ultra-violet radiation-based device, highly dynamic robotic gripper and sensing system and autonomous heavy-duty cleaning robot. The use of these robots significantly improved the safety and the quality of healthcare management. Robots were extensively used to control the COVID-19 pandemic, reducing the number of infected patients and casualties.

Infection cluster detection.

Two papers examined the use of automated systems for infection cluster detection in the hospital setting [28, 29]. Aghdassi et al. described an automated cluster alert system (CLAR), based on number of detected isolates, type of pathogen and resistance, sampling material and ward interested [29]. CLAR identified a high number of alerts, validated by IPC physicians. In a similar way, Stachel et al. implemented an automated surveillance system to detect hospital outbreak, called WHONET-SaTScan, which proved to be a useful addition to their regular IPC program [28]. It works combining a statistical software (WHONET) and a software managing microbiology laboratory data (SaTScan).

Air quality control.

Only one article dealt with air quality control, focusing their effort in the operating rooms (ORs) [30]. Colella et al. developed a fuzzy inference system (FIS), which assesses the OR air quality and provides real-time alarms, making HCWs aware of potential risk. The risk level is decided by FIS considering four parameters, namely particle count, temperature, relative humidity patients and HCWs movements. Typically, FISs are an important part of fuzzy logic systems that perform decision-making and are mainly based on the Mamdani or Sugeno frameworks [34].

Correct use of PPE.

Another important aspect of IPC is the correct use of PPE, Preda et al. realized an AI-PPE system, with the goal of analyzing donning and doffing with real-time feedback [31]. They validated this technology comparing it to the gold standard, i.e., double buddy system. Furthermore, they included in the study participants with heterogeneous visual characteristic (i.e., people with different ethnical backgrounds, age, sex, etc.) in order to lower the risk of AI bias [33].

Quality appraisal

The outcome of the MMAT quality analysis can be found in the Supplementary Table A3. Most criteria were met by all studies. Most of the issues rose from the quantitative non-randomized studies. Nine studies did not take into account confounders in the design and analysis, while for one study this was unclear. Addressing confounders is important to avoid misinterpretation of findings, due to spurious associations [35, 36]. Moreover, for six studies it was unclear whether the participants were representative of the target population. The lack of clear descriptions of the target population and of the sample can lead to erroneous conclusions, and ultimately to nonresponse bias [37]. Potential bias could be present in Akkok et al.'s study, as they could not prolong its duration due to HCWs' refusal, additionally there is no data available for consultants' HH events.

Discussion

This systematic literature review allowed to highlight four points of discussion, arising from the selected paper that led to a wider proposal for the conclusion. Firstly, the main focus of the current literature on the topic is on IPC options, specifically on hand hygiene and UV disinfection rather than the use of robots and IoT. The retrieved and selected articles about robotics are very generic, outlining their general applications, but not giving specific details on the specific field where such solutions may be most required and/or will add most value, benefits and dis-benefit. Overall, HH is the most debated theme and also the one with the most impressive technological advancement (and probably funding). The latest advancement in technologies, AI and IoT could and should be exploited more to allow for autonomous robots and remote operations in healthcare.

Secondly, HCWs are the first recipients and users of the health technologies reported and described in this systematic literature review. However, it seems that usability engineering principles are often overlooked, as they are not usually involved in the co-creation and co-design of such technologies. Moreover, HCWs lack awareness and education on the importance of complying with the use of such technologies, that if not well prepared could be lacking [27, 38] or that could decrease after the emergencial period [21]. To accelerate the HCWs response, there might be a need to transform the IPC routine into a habit for them [27, 39]. To monitor and improve HCW's IPC routines in hospitals, Jeanes et al. [40] developed and tested a quality improvement tool, which received good feedback from the participants. When devising and designing such solutions, more attention should be paid towards the fact that HCWs may not like the idea of being tracked and monitored during their already very difficult and stressful professional activities. It is also noteworthy that the intensification of practices stemming from these solutions could have long-term side effects (e.g., psychological effects such as mysophobia and compulsive hand washing) [41]. Strictly linked to this, but not directly mentioned in the collected literature, there is the need to make doctors more aware and expert of state-of-the-art healthcare technologies, not only by involving them in the design of the technological solutions used in their professional practice, but also by re-designing their academic education paths. This has already started in some countries (e.g., Italy), where medical students will be offered relevant biomedical engineering education spread across their medical studies in order to obtain both a full degree in Medicine and a Bachelor of Science in Biomedical Engineering. The trailblazer for this, in Italy, was Humanitas University in collaboration with Polytechnic University of Milan [42]. Similarly, other universities are joining forces to offer medical students a path of excellence [43] to expand the knowledge of future doctors on new technologies that increasingly impact clinical activity, both diagnostic and therapeutic.

This urgent need to bring doctors closer to advanced health technologies and to improve the robot-human relation also relates to the fast technological enhancing that hospitals are experiencing, on the wake of Health 4.0. In fact, hospitals are undergoing a revolution increasingly becoming more sensorised and robotized, relying on innovative high-tech tools, as portrayed in the selected papers. As mentioned in the introduction, one leading example is that of the European (Horizon2020) project ODIN [11]. This project is leveraging AI-based technology to transform the future of healthcare delivery in leading hospitals in Europe. In particular, its three areas of intervention are enhanced hospital workers (i.e., exploring how to empower HCWs with appropriate technologies to enhance their skills and support their daily work), enhanced robots (i.e., exploring how to automate hospital processes that no longer need humans or can benefit from automation), and enhanced location (i.e., exploring how to instrument medical locations for enabling them to proactively support hospital processes). The project relies on five European Pilots namely the University medical centre of Utrecht, the Charité university hospital in Berlin, Medical University of Lodz, University hospital campus biomedico in Rome and Hospital clinico San Carlos in Madrid. There are seven clinical use cases, i.e., aided logistic support, management of medical devices and sites, AI-based support systems for diagnosis, clinical tasks and patient experience, automation of clinical workflows, inpatient remote monitoring, and disaster preparedness.

Furthermore, from the included papers, it is clear that all the emerging technological solutions are not easy to implement, because they are extremely advanced, expensive and their envisioned use environment is up to relevant international standards and minimum requirements. This means that none of them is suitable, as it is, for low-resource settings, i.e., contexts that are severely hindered by numerous challenges and characterise both the so-called high-income countries, perhaps in the more rural and peripheral areas, and low-income ones [44, 45]. Although these solutions lack a contextualised and frugal perspective, they should not be overlooked, as they are the main gears pushing forward the frontier of progress, and, as COVID-19 clearly demonstrated, different parts of the worlds can be affected differently and generalist approaches risk being unnecessarily expensive and impossible to achieve uniformly globally [46]. Nevertheless, it is clear that contextualised and frugal design approaches should be negotiated with the need for uniformity and equality, a utopic idea towards which to strive.

Conclusions

This systematic literature review demonstrates that IPC practices within hospitals mostly focus on HH and UV devices for disinfection. Not much has been done in regard to the use of IoT, AI, big data technology, robots in the field of IPC within nosocomial settings. This review highlights how most of the literature regarding automation and robots for IPC in hospitals is either outdated or not very impactful, despite the recent COVID-19 pandemic. Nonetheless, the review allowed to highlight five main areas that were presented and discussed. Among the main findings, it was noticed that there is no adequate consideration of HCWs in terms of awareness and training with respect to the design and use of healthcare technologies that impact on their daily work and may have repercussions on their everyday lives. However, their direct involvement in technology co-design and training is strictly necessary, since Health 4.0 is dramatically revolutionizing the way hospitals and HWCs work, leading the digitalization of healthcare. As mentioned before, one of the trailblazing European projects in this remit is ODIN. Although this is currently mainly concerning high-income countries, which are pushing forward the frontier of progress for finding solutions and novel approaches for future pandemics, research priorities should also be considering how to implement similar or more contextualized options for lower income countries.

Acknowledgments.

None.

Availability of data and materials

The datasets used and/or analysed during this study are available from the corresponding author on reasonable request.

Conflict of interest statement

The authors declare that they have no competing interests.

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