Innovation for infection prevention and control—revisiting Pasteur's vision

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See **Comment** page 2163 and 2164 and 2166

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Louis Pasteur has long been heralded as one of the fathers of microbiology and immunology. Less known is Pasteur's vision on infection prevention and control (IPC) that drove current infection control, public health, and much of modern medicine and surgery. In this Review, we revisited Pasteur's pioneering works to assess progress and challenges in the process and technological innovation of IPC. We focused on Pasteur's far-sighted conceptualisation of the hospital as a reservoir of microorganisms and amplifier of transmission, aseptic technique in surgery, public health education, interdisciplinary working, and the protection of health services and patients. Examples from across the globe help inform future thinking for IPC innovation, adoption, scale up and sustained use.

Introduction

During the 17th century in Europe, hospitals accommodated poor and sick people, often with incurable diseases, in large dormitories together with older people, children, and healthy alike. A need for hygiene was felt by many, and despite some architectural measures to improve air quality, infections persisted and so-called hospital rot continued to kill. The collective work of contemporary physicians, nurses, and scientists, including Ignaz Semmelweis on hand hygiene, Robert Koch on microorganisms and infection causality, Ernst von Bergmann and Joseph Lister on the asepsis in surgery, Florence Nightingale in implementing innovative concepts in nursing, and Louis Pasteur with his demonstration against the theory of spontaneous generation, eliminated alternative theories (that of miasma in particular).[1]

Pasteur's era is characterised by the acceleration of knowledge on infection prevention and control (IPC) and the early formation of practices that we now take as central to safe health care. Louis Pasteur, although a chemist, was a key contributor to modern IPC, public health, and much of modern medicine. His non-medical background, and use of an evolutionary process of learning by doing, provided a fresh approach to medicine and the health-care system. Being a scientist and not a surgeon did, however, pose other challenges in terms of acceptance of ideas from the medical world. After being elected to the Académie Nationale de Médecine (National Academy of Medicine, Paris, France), he was invited to visit a hospital for the first time. Pasteur immediately perceived the greatest IPC challenges to be in health-care settings and associated with advances in medicine and surgery. His near obsession in the fight against microbes is as relevant today because of the levels of drug resistance we now see globally. His observation of health-care workers showed that they ignored the presence of microbes. Without Pasteur's work on developing and implementing IPC methods, the tremendous advance of medical and surgical techniques by the end of the 20th century would have been impossible.[2] Despite substantial progress and increased efforts in IPC in the past two centuries, health-care-associated infections (HAIs) remain a substantial global burden.[3,4] In low-income countries, the prevalence of HAIs was estimated to be 15·5 per 100 patients, much higher than proportions reported from Europe (6·5%) and the USA (3·2%).[3,5,6] In 2017, the European Centre for Disease Prevention and Control calculated that 8·9 million episodes of HAI occurred every year in patients admitted to acute care hospitals and long-term care facilities in EU or European Economic Area countries.[5] HAIs generate 16 million extra days of hospital stay for a direct cost of €7 billion per year for hospitals, nearly 100 000 attributable deaths, and 501 disability-adjusted life years per 100 000 general population each year.[4] Prevention of HAIs reduces the need for antimicrobials, contributing to mitigate the burden of bacterial antimicrobial resistance in health care.[7]

Innovation in health care refers to the development of a new process, policy, product, or programme that increases quality, impact, and efficiency.[8] Pasteur's drive for innovation was as much in response to economic problems as to health science questions and also for a range of industries. A multidisciplinary approach including (micro) biology, agriculture, medicine, hygiene, and engineering meant that his discoveries and innovations improved the medical and health industry as well as beer, wine, farming, and silk industries in France, with learning between these industries. For IPC, value encompasses the public health and economic case for policy makers, the patient-centred case for public and patients, the scientific and ergonomic case for end users (professionals and health-care organisations), and the return on investment for innovators. Value at the global level additionally means alignment with the Sustainable Development Goals, including the sustainability and green agenda requiring input from industries outside of health care.

In honour of the 200th anniversary of the birth of Louis Pasteur, we present examples of Pasteur's vision and six key areas of pioneering work that had implications for IPC and how we need to revisit these concepts when innovating to prevent HAI.

Pasteur's vision of the hospital as a reservoir of microorganisms

Louis Pasteur showed that microbes are everywhere; in water, in the air, on objects, and on the skin, and that some of them are responsible for illnesses (figure 1). In

1862, he stated that "*les poussières de l'atmosphère renferment des micro-organismes qui se développent et se multiplient*" ("the dust in the atmosphere contains microorganisms which develop and multiply") and "*les liquides les plus putrescibles restent inaltérés, si après les avoir chauffés, on les laisse à l'abri de l'air, donc de ces micro-organismes*" ("the most putrescible liquids remain unaltered if, after heating them, they are left protected from the air, and therefore from these microorganisms").[9] Louis Pasteur, therefore, postulated and helped show that germ transmission could result from a contaminated environment.

Complex interactions occur between the microbiota of hospital environmental surfaces and that of hospital staff and patients.[10] Distinct ecological niches of microbes and antibiotic resistance genes coexist, characterised by the formation of biofilms and human–microbiome-influenced environments.[11] For example, admission to a room previously occupied by a patient infected or colonised with a specific pathogen is a risk factor for acquisition.[12] On dry, inanimate surfaces, *Staphylococcus aureus,* including methicillin-resistant *S aureus* (MRSA) can survive for up to 7 months; *Clostridioides difficile* spores for up to 5 months; *Enterococcus* spp, including vancomycin resistant strains for 5 days to 4 months; *Acinetobacter* spp for 3 days to 5 months; and *Pseudomonas aeruginosa* for 6 h to 16 months.[13] Sink drains are a major reservoir for multi-drug-resistant organisms (MDRO) with direct links to patient infections.[14] In hospitals, patients acquire room-associated taxa during the first days of hospitalisation but then transmit their own microbiota to the patient room during their hospital stay. To improve the prevention of HAIs, we need a better understanding of the characteristics and dynamics of the hospital microbiome and to establish the feasibility of systematic surveys to target resources for preventing infections.

The hospital's infrastructure and architecture have an influence on HAI rates. Many topics still remain controversial in this area, such as the effect of single room design on the reduction of cross-transmission of MDROs.[15] Temperature, humidity, and the indoor ventilation system in hospital buildings affect various infectious organisms, particularly respiratory pathogens. Although evidence indicates an effect on the infection rate in several situations, the optimum ranges of these parameters at different spaces in hospitals are yet unknown.[16] Simulation approaches considering multiple environmental parameters can model the efficacy of different design and engineering solutions for optimum ventilation strategies.[17]

Traditional environmental disinfection methods are notoriously inefficient for decontamination.[18] Hospital environmental disinfection is complex and highly dependent on the product, application technique, equipment, personnel and training, type of surface, and level of contamination.[19] Implementation science offers the opportunity to consider this complex process by using methods and strategies that facilitate the uptake of best practices at the organisational level.[20] Innovative technologies such as disinfectants, steam, automated dispersal systems, and antimicrobial surfaces offer an alternative strategy for environmental hygiene purposes.[21] The use of antimicrobial surfaces needs careful consideration. Evidence is still needed on their contribution in reducing HAIs. Cost–benefit analyses are required, involving resources for installation, their durability, the possible toxicity, resistance, allergenic properties, surfaces to coat, and relative contribution of self-disinfecting surfaces to hand contamination.[22]

Pasteur's vision of the hospital as an amplifier of transmission

After Pasteur's demonstration of the existence of microbes that affected grape juice, the recognition that many diseases were accompanied by specific microorganisms was becoming more accepted.[23] Around this period (1875), after an episode of 64 fatalities caused by childbirth fever

Search strategy and selection criteria

We searched the Cochrane Library, MEDLINE, and EMBASE from Jan 1, 2012, to Oct 7, 2022. The literature search was conducted to source literature in the six key innovation areas grounded in the work of Louis Pasteur, and to understand if the literature on innovations in infection prevention and control is aimed at wider audiences or confined primarily to infection prevention and control and infectious diseases audiences. We used search terms related to the prevention of health-care-associated infection prevention and hospital microbiome: "air ventilation", "antimicrobial surfaces", "sterilisation", "cross-transmission", "hand hygiene", "standard precautions", "contact precaution", "whole-genome sequencing", "antimicrobial resistance surveillance", "dressing", "surgical site infections", "education and training", "multidisciplinary", "health-care worker vaccination", and "patient vaccination". We focused on publications in the past 10 years but did not exclude commonly referenced and highly regarded older publications. We also searched the reference lists of articles identified by this search strategy and selected those we judged relevant. Review articles and book chapters were cited to provide readers with depth and context. Cases of success were selected with the expertise of the international authors in addition to cases identified by a wider group of experts that contributed to the research roadmap for infection prevention and control and addressing antimicrobial resistance. We identified types of innovation in the infection prevention and control (IPC) areas defined by Pasteur on the basis of an analysis of his biography, writing, declarations and publications. Six IPC areas were found relevant: (i) hospital as a reservoir of microorganisms, (ii) hospital as an amplifier of transmission, (iii) asepsis in surgery, (iv) interdisciplinary collaborations, (v) public health education, and (vi) immune protection against health-care associated infections. For figure 3, we retrieved the bibliographical data by searching PubMed, Ovid MEDLINE, Ovid EMBASE, Ovid Nursing Database, Global Health Policy and Management, Cochrane Library databases, Health Management Information Consortium, Maternity and Infant Care Database, Social Policy and Practice, PsychInfo, and CINAHL, from Jan 1, 2012, to Oct 7, 2022, for the terms: "infection prevention" OR "infection control" AND "Innovat" AND NOT "Covid". We excluded animal models; studies of HIV, tuberculosis, Zika, Ebola, influenza, and vector-borne diseases; cost analysis studies; and vaccination studies (because it was outside of scope of this paper and included in another article in this issue). Our search results yielded 1979 studies, of which 484 duplicates were removed; 1495 titles were screened for relevance; 617 studies were irrelevant; and 878 studies were included and coded.

Figure 1: **Louis Pasteur's vision and legacy in infection prevention and control**

in the Paris Maternity Hospital, Pasteur strongly proposed that the infection was being spread by physicians and hospital attendants. Although Pasteur never mentioned that the hands of the obstetricians could transmit the disease, his proposition that surgeons' and midwives' hands, instruments, and dressings were responsible for transmitting germs from a sick woman to a healthy woman was implicit.[24]

> "*Il me vient cette idée que le corps étranger quand il amène le pus, ce qui n'est pas constant, doit apporter un germe, lequel germe serait cause de la formation de pus.*"
>
> "I have this idea that the foreign body when it brings pus, which is not constant, must bring a germ, which germ would be the cause of the formation of pus."
>
> *Louis Pasteur*

> "*Au lieu de s'ingénier à tuer les microbes dans les plaies, ne serait-il pas plus raisonnable de ne pas en introduire?*"
>
> "Instead of striving to kill the microbes in the wounds, wouldn't it be more reasonable not to introduce any?"
>
> *Louis Pasteur*

Pasteur introduced, with others (such as Semmelweis and Nightingale), the current IPC concepts of standard precautions and isolation (contact precautions) to mitigate cross-transmission in hospitals. Hand hygiene appeared as a major shift in thinking to prevent HAI at the time of Pasteur. He was described as a fanatic of hand hygiene himself and being almost obsessively concerned with the risk associated with hand-to-hand as well as hand-to-environment contact. We now know that health-care workers' hands become progressively colonised with commensal flora and potential pathogens during patient care.[25] However, two centuries after Pasteur, relatively few data are available regarding the types of patient care activities that result in transmission of patient flora to health-care workers' hands. A second shift occurred in hand hygiene during the early 2000s: the change from handwashing with soap and water to using alcohol-based hand rubs.[1] Alcohol-based hand rub appeared as a revolution in patient care due to the effectiveness, availability at point of care, and the better tolerance by skin than soap and water.[26] This change led to an improvement of health-care worker compliance from 48% to 66% on average, and a parallel reduction was observed in HAI rates and the spread of MRSA.[27] Due to the commitment of WHO and the high level of international involvement, hand hygiene compliance became a key indicator of patient safety and quality of care in health systems worldwide.[28] Local production of alcohol-based hand rub based on the formulations recommended by WHO provides a low-cost alternative to commercially produced hand rubs that might be unavailable or unaffordable in some countries.[29] Despite substantial improvements, innovative methods addressing both the structural and behavioural aspects of hand hygiene are required.[30] The implementation of standard precautions requires adequate infrastructure bringing together water, sanitation, and hygiene (WASH) facilities. In Africa, WASH facilities are suboptimal (eg, 58% of health facilities in Africa have a protected source of water on premises and 22% of health facilities have no sanitation services) in most settings and represent a major concern in achieving consistent breaking of infection transmission.[31] Therefore, IPC and WASH are complementary interventions in health facilities, both during outbreaks and in non-outbreak situations.[32]

In addition to enhancements of hand hygiene, surveillance screening to identify colonised patients and the implementation of contact precautions (single room and glove and gown use) helped mitigate the spread of skin organisms such as MRSA.[33] Since the end of 2000s, this approach has been challenged by the global spread of emerging pathogens such as multi-drug-resistant Enterobacterales (MDR-E) in hospitals, nursing homes, and the community. MDR-E acquisition of short duration (30 days median) is frequent in travellers to endemic regions in the world.[34,35] Moreover, MDR-E household co-carriage is frequent, suggesting intrafamilial acquisition.[36] In Africa, 17% of pregnant and post-partum women (22% in the community and 14% in hospital setting) were estimated to be colonised with extended-spectrum beta-lactamases producing Enterobacterales.[37] Health-care facility connectivity in health care networks of patient transfers is correlated with MDRO incidence, underlining the importance of coordinated control measures at the regional scale.[38] Failure of one hospital's IPC measures can therefore affect an entire network of hospitals sharing patients. The coordination of control measures that are still suboptimal needs to be improved at all scales. The surveillance of MDRO in health-care facilities is also challenged by the extensive nature of the epidemiology. New methods based on the microbiological analysis of wastewater in these settings appear promising to accurately identify and describe the epidemiology of the antimicrobial resistance.[39] Whole-genome sequencing has identified heterogeneity within pathogen species, with some subtypes transmitting and persisting in hospitals more than others.[40] Whole-genome sequencing has shown that multiple introductions of these pathogens from the community might play a greater role. Real-time use of whole-genome sequencing in hospitals could allow IPC teams to identify transmission and target interventions, and provide surveillance and infection control benchmarking.[41]

Aseptic technique and the origins of modern surgery

In 1878, Pasteur's speech addressed to surgeons from the French Academy of Sciences: "If I had the honour of being a surgeon, penetrated as I am by the dangers to which the germs of microbes expose...not only would I only use perfectly clean instruments, but after having cleaned my hands with the greatest care and having submitted them to a rapid buckling...I would only use lint, strips and sponges previously exposed to air brought to a temperature of 130 to 150°C; I would only ever use water that would have undergone a temperature of 110 to 120°...".[42]

In England, Joseph Lister, a surgeon contemporary of Pasteur, understood that putrefaction was based on the same principles as fermentation described by Pasteur.

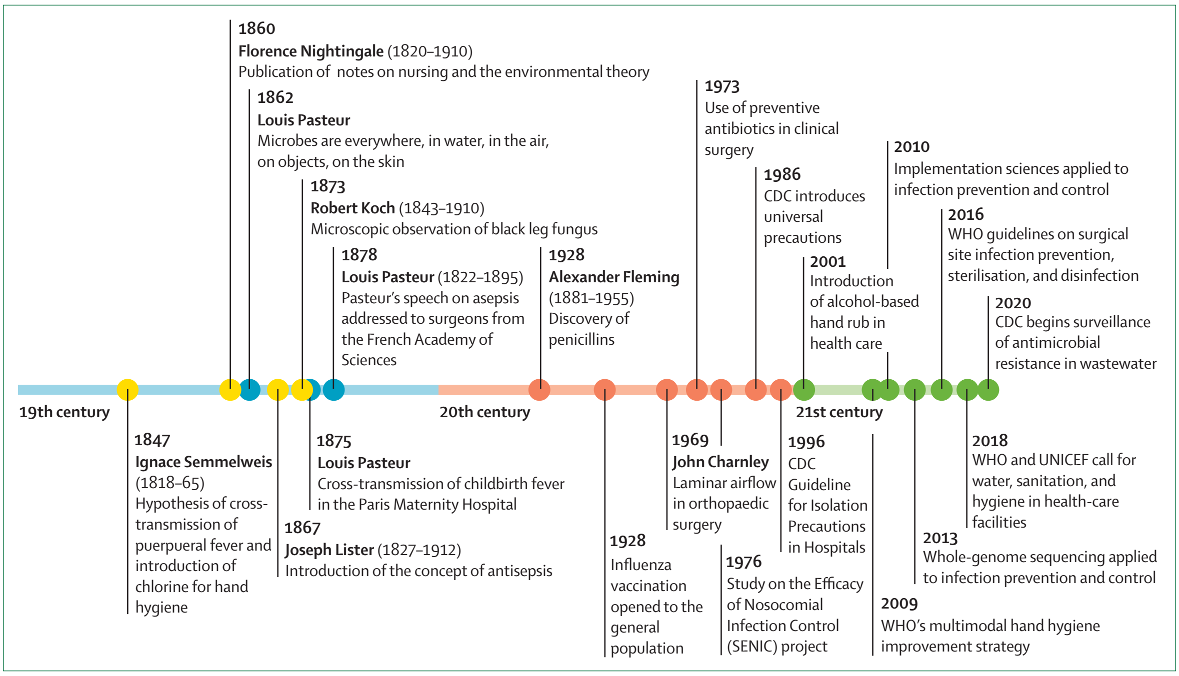

Figure 2: **Timeline of selected innovations related to Pasteur's vision**

Lister introduced the concept of antisepsis by developing a spray of carbolic acid around the operating table to kill microbes before they reach patient's wound (figure 2). By this innovation, Lister reduced the in-hospital death rate from 40% to 15%.[43] Pasteur went further by developing the concept of asepsis by finding ways to prevent pathogens from entering the wound. Pasteur warned surgeons and obstetricians to wash their hands, use heat to sterilise their instruments, and sterilise objects and dressings.

The prevention of surgical site infections involves the application of antiseptics to the skin, and in some cases the decolonisation with topical antibiotics.[44] However, pre-operative bathing remains highly debated, and controversies persist regarding the type of alcoholic antiseptic to use (povidone iodine *vs* chlorhexidine) for surgical site preparation and the decolonisation of *S aureus* carriage (eg, the cost-effectiveness in orthopaedic surgery).[45] Their respective effectiveness, and the collateral damages they might cause in terms of bacterial resistance, hypersensitivity reactions, and co-selection for antibiotic resistance is still questioned. The solution might come from alternative compounds or concepts (ie, vaccination or immunotherapy) leading to fewer adverse effects.

In 1883, following Pasteur's vision, a French surgeon, Octave Terrillon, sterilised instruments and dressings by boiling or by dry heat autoclave. Sterilisation and decontamination of instruments and medical devices became a critical measure to prevent HAIs. Defective sterilisation and decontamination still occur in many settings.[46] Inappropriate reuse of disposable medical devices is common practice and the procedures to clean and decontaminate these devices are sometimes inadequate and not standardised. The processes of sterilisation and decontamination are complex. They require specific infrastructure and equipment and involve several steps that need to be correct, from device collection to receipt by the unit, processing, storage, and distributing them throughout the facility. Of utmost importance are quality control procedures to assess the correct functioning of the equipment.[47] Innovative sterilisation methods based on sunlight heat might provide widespread solutions for securing the use of medical devices, with the collateral advantage of using sustainable and green energy.[48]

Surgical site infections are among the leading cause of HAI globally.[4,49] Commensal flora of operating room staff have been found in the air during procedures,[50] and identical *S aureus* strains were found in the air and in the wound.[51] However, the link between the air contamination by operating room staff and the occurrence of surgical site infection has never been clearly shown. Recent events proved that medical devices present in the operating room (ie, heater-cooler devices or air-forced warming systems) might appear as a reservoir of microorganisms or compromise surgical asepsis.[52,53] Most operating rooms in high-income countries are now equipped with ventilation systems filtering the air and providing positive pressure. The current available evidence and the cost of laminar airflow systems in comparison with conventional ventilation systems are still controversial.[54] The methodological complexity to address this issue (ie, low number of surgical site infections in clean surgery, with many confounding factors) will require innovative methods, such as simulation adopted by the aeronautical industry.[55] In addition to technical aspects of surgical site infection prevention, the intraoperative behavioural side is poorly explored. Studies suggest that operating room staff traffic flow (movements and doors opening) compromises patient safety by: (1) increasing the air microbial contamination,[56] (2) disrupting the ventilation efficacy, and (3) interrupting the surgical team's concentration.[57] Innovative approaches based on monitoring systems and social sciences might help improvement efforts.

Surgical wounds are often covered with a dressing that acts as a barrier between the wound and the outside environment. Some dressing types, such as negative pressure wound therapy, silver-containing dressings, or antiseptic impregnated dressings, appear as promising ways to prevent surgical site infections and reduce risk of death.[58] However, the relative effectiveness of these types of dressing, in comparison with standard dressings or not dressing at all, remain scarce. Innovation in wound dressing might come from providing clinicians with practical tools, a basic understanding of the processes of wound healing and wound bed preparation to match the ideal cost-effective dressing to the particular type of wound to be managed,[59] and smart wound dressings with sensors assessing the healing process.[60] Collaborations that show promise include those between clinicians and scientists from physics, materials science, nanoengineering, and stem cell biology, to manufacture dressings that serve as physical, chemical, and antimicrobial barriers, as well as devices for growth-factor and cell delivery.[61]

Multidisciplinary and cross-boundary working and leadership

Pasteur's highly multidisciplinary approach, bringing together engineering, chemistry, and medicine, led to major innovations in IPC. In contemporary times, we see applications in the design of surfaces for hospital infrastructure and surgical instruments, but also in advanced modelling of patient flows through hospitals. Less advanced is our tracking of patients through the health system. A recent example of cross-industry translation is the adoption of the surgical safety checklist from the aviation industry.[62] The checklist by itself appeared not sufficient to improve quality and outcomes. The cross-boundary translation of such tools to medicine required an approach considering human factors in the safety cultures of institutions and systems. The use of multimodal strategies to implement IPC activities recognises this approach across organisations and systems. The WHO multimodal implementation strategy for improving hand hygiene practices brings system change, training and education, monitoring and feedback on IPC practices, reminders and communications in the workplace, and strengthens a culture of safety.[63] The field of social sciences has helped to bring a greater recognition of the roles of social norms and behaviours in good infection control practices. Additionally, the roles of utility theory and regulation in influencing behaviours at an institutional level are additional disciplinary approaches adopted in some national-level strategies. The evidence of effectiveness of such strategies remains to be evaluated systematically.

Scientific articles regarding innovation development and implementation in infection control in the past decade are still largely confined to clinical and infection control journals, with very little in mainstream health management and social science journals (figure 3). There is, however, widening reach to other clinical audiences and some multidisciplinary audiences. The learning between high-income and middle-income countries is still skewed towards high-income settings. The term innovation, if we are very critical, seems overstated, being used to describe mainly single, technological innovations rather than system or transformational changes. There are notable examples however, with system level innovations for new technologies and processes and innovation for embedding and scaling up interventions that have a well-established evidence base (panel; the examples are the result of purposeful sampling to highlight progress and challenges in multidisciplinary and cross-boundary working and in scale up of effective innovations).

Pasteur's vision of health-care settings as a platform to spread public health education

Louis Pasteur said that "*L'hôpital doit être le lieu de la formation publique sur l'hygiène, aidé en cela par les assistantes sociales et les infirmières visiteuses des dispensaires qui vont au-devant de l'humanité souffrante*" ("The hospital must be the place of public education on hygiene, helped in this by social workers and nurses visiting dispensaries who go to meet suffering humanity").[69]

The mounting clinical and technical complexity of IPC, together with the growth in the expertise and scope of different professions, demands a closer interdisciplinary cooperation. To assist this collaboration, IPC practitioners benefit from education competencies that recognise their unique professional expertise but also reflect shared areas of decision making.[70] Technological advances, such as virtual reality and simulation,[71] and pedagogical innovations embracing arts-based approaches facilitate joint educational experiences among professionals.[72]

Attention to the education and self-efficacy of patients and citizens in IPC interventions has surged, acknowledging the important role of patients as peers, not only in the community and as part of health protection interventions, but in hospital.[73] Although it is clear that patients can, and want to be, useful assets for IPC interventions, further research needs to explore cultural and contextual sensitivities to this participation,[74] avoiding the potential for exploitation.

Education undoubtedly remains an essential support for patient participation in IPC. However, efforts in this area would need to address not just any gaps in knowledge, but also improve underlying determinants of suboptimal health literacy (how people use information to make decisions about health and services).[75] If this is not the case, then there might be little progress in addressing the misinformation and disinformation that surrounds some infection-related topics, from the origin of emergent pathogens to effective therapies.[76] Nowadays, Pasteur's advocacy for hospitals to be education hubs for society

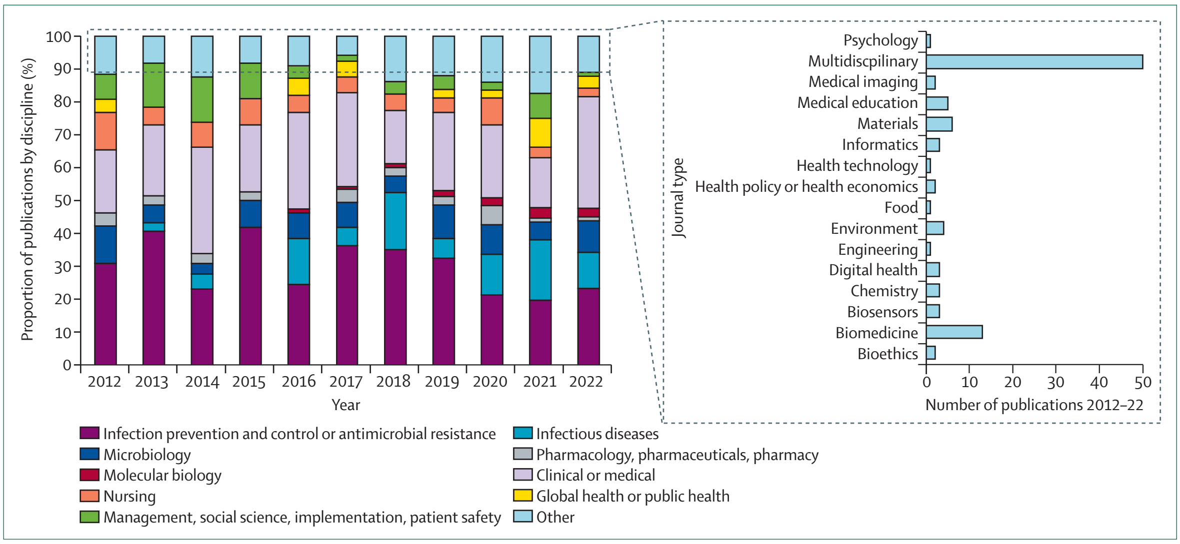

Figure 3: **Dissemination of innovation development and implementation**
The data show a positive trajectory to wider clinical speciality audiences but restricted learning in management and social science outputs.

Panel: **Selected examples of innovative approaches at the systems level to mitigate structural barriers and workforce limitations**

Development and implementation of new technologies and processes

Laboratory Information Systems for low-income and middle-income settings[64,65]

Innovation stage: co-development, establishing technical capacity requirements before demonstration phase

Absence of or poor laboratory data management severely hinders antimicrobial resistance surveillance in low-income and middle-income countries. This innovation aims to circumvent physical laboratory-based traditional surveillance systems for culture and susceptibility testing by the development and access to open-source laboratory information management system software.

Virtual Wound Care Command Centre for high-income settings[66]

Innovation stage: implementation and evaluation for feasibility to scale up

Geographically dispersed communities and low numbers of a specialist workforce in Australia are challenges to effective wound care post-surgery and for house-bound older populations. This innovation comprises access for clinicians to an expert wound specialist service using digitally enabled application for wound analysis, decision making, remote consultation, and monitoring.

Approaches to routinise use of well-established innovations

Infection control practices in hospital settings

A Systems Engineering assessment of barriers and facilitators[67]

The high turnover of nursing staff in Manila, Philippines, necessitates constant training due to a weak organisational memory. The Systems Engineering Initiative for Patient Safety approach was used to establish which technological monitoring and reminder systems might help reinstate this hospital as once a positive outlier for effective infection prevention and control in the private health sector.

Preventing catheter-associated urinary tract infections in nursing home residents[68]

Employing technical and socio-adaptive interventions

A national programme implementation in 48 states in the USA. Programme enhancements included a technical bundle: catheter removal, aseptic insertion, using regular assessments, training for catheter care, and incontinence care planning, as well as a socio-adaptive bundle emphasising leadership, resident and family engagement, and effective communication.

about infections would have to resolve the challenges posed by social media platforms and the partisan use of evidence.[77]

However, the central role allocated by Pasteur to health organisations for the education of patients resonates well with ideas about hospitals as anchors of the communities they serve,[78] as social and economic engines for the betterment of the living and working conditions of these communities, and with a clear focus on health improvement. Models in which hospitals closely integrate with other primary and secondary providers, together with local authorities, might enable more effective and holistic policy responses to the complex causes and consequences of infections.[79]

Attention to the unmet needs of vulnerable populations and individuals (between and within countries) remains highly relevant because of the interplay of clinical, socioeconomic, commercial, and political determinants of infections.[80] Interventions to arrest the emergence and re-emergence of infectious threats and implement optimum IPC measures benefit from the prosocial behaviours encouraged by social cohesion, greater equity in terms of access, and reduced inequalities in outcomes.[81]

Vaccines as armoury to protect health services and patients

Pasteur's discovery of vaccines had an indirect positive effect on health-care services. Vaccination of health-care workers prevents the risk of disease to them and to patients,[82] and keeps the health-care system functioning. For example, US data show that the COVID-19 case incidence ratio during periods after vaccination versus before vaccination decreased by 53% in adults aged 65 to 74 years (95% CI 50–55) and 62% in adults aged 75 years and older (95% CI 59–64). Similar results were shown with emergency department visits decreasing by up to 77% in people older than 75 years, therefore preserving health-care capacities.[83] Secondly, it has been long recognised that health-care workers are an occupational group at high risk of acquisition of diseases preventable by vaccination.[84] HAIs such as influenza, measles, hepatitis, and whooping cough emphasise the importance of immunising health-care workers. Presenteeism, defined as working while being ill, is common among health-care workers, even in people who work in high-risk settings, placing their patients and colleagues at risk.[85] Influenza is a major driver of absenteeism in the health-care workforce during winter, when demand for health-care services peaks.[86] Cost-effectiveness analysis suggests that an employer-provided influenza vaccination programme is a financially favourable strategy for reducing costs associated with employee absenteeism, presenteeism, and medical care due to influenza.[87] Despite long-term recommendations for influenza vaccination of health-care workers, uptake rates remain largely suboptimal in most countries.[88] Vaccine hesitancy exists in health-care workers, and there are barriers to immunisation acceptance.[89] Occupational health services have an important role in health-care-worker vaccination. The resources and involvement of this speciality require particular attention. Mandatory vaccination policies are not a new concept. Available evidence indicates that no single intervention other than mandatory vaccination policies can achieve high (>90%) and sustainable influenza vaccination rates among health-care workers.[90]

Vaccines, passive immunisation, and advances in monoclonal therapies are probably among the most promising innovations to decrease the overall burden of HAIs.[91] Immunological approaches have been considered for more than a decade. However, vaccine development for HAIs has been hampered by many factors, such as the immune response of at-risk patients and the endogenous form of targeted pathogens, such as *S aureus*.[92] For most of the pathogens involved in HAIs, vaccines are not available, and the development of effective vaccines for *S aureus* or gram-negative bacteria remains challenging.[93] For *C difficile*, the goal of obtaining a preventive vaccine seems to be near.[94] Results of large advanced phase trials will provide results on the effectiveness, cost, and tolerance. Remaining challenges will be the acceptance of these new vaccines by patients and prescribers. Despite little clinical evidence, antibody-based therapy represents a promising therapeutic option, offering a pathogen-specific antibacterial alternative to antibiotics in the acute-care setting.[95]

Innovation from IPC with application to the wider health system

Innovation to address the first of Pasteur's discoveries, that the hospital, and health-care itself, is a major source of infection and a threat to patient safety, leads us to strategies that minimise hospital stay, or keep patients out of hospitals altogether. We need to look at health-system-level transformation; advances in day surgery and step-down services, but also the developments in virtual wards. From China, we can learn from social care, where virtual care homes have been implemented at scale.[96] In low-income settings, infrastructure is likely to take decades to build and innovation in laboratory information-management systems might in fact supersede some of the efforts at data integration in high-income settings.[64] Advances in decision support, machine learning, and artificial intelligence in infection diagnosis and management have particular relevance for low-income and middle-income countries.[97] By looking at innovation as a means of strengthening health systems, the social, economic, and public health value proposition is fulfilled. But for sustained impact, any programme of learning must also involve the wider public through mechanisms of patient generated data; some excellent examples were seen during the COVID-19 pandemic, such as the Zoe web-based mobile application in the UK and the Aarogya Setu application in India.[98]

Future challenges to infection control

In the context of ageing populations, patients in modern hospitals are increasingly sicker, with multiple comorbid conditions, and increasingly receive therapies that modify both the immune system and the personal microbiota. Outpatient and day-care procedures also grow increasingly complex and invasive. IPC in the health-care setting traditionally relied on minimising the cross-transmission of bacteria from patients and environment by way of health-care-worker hand hygiene. Although many advances exist in infection prevention, the current science probably prevents only up to 55–70% of all HAI.[99]

New strategies and solutions are required to further patient safety. Future challenges to IPC are multiple and will require broad, collaborative, multidisciplinary efforts with creative thinking in the spirit of Pasteur. For current infection prevention strategies, increased emphasis is required on implementation and organisational sciences to better influence reliability in the application of safety measures. Innovation in IPC will also come from broader collaboration with colleagues in informatics to engineer for effective prompts within electronic medical records for the removal of unnecessary devices and minimisation of unnecessary antibiotics. Technologies such as sensor badges worn by health-care workers to monitor hand hygiene could result in improved practices.[100] Improvements in personal protective equipment are required to maximise the ease of donning, doffing, and proper use. In addition to ongoing advances in antisepsis, disinfection, sterilisation, and cleaning of the health-care environment, a greater understanding is required of the human microbiome to minimise its disruption and maximise its protective effect. These innovations in IPC must be coupled with the ongoing development of new antimicrobials to treat resistant infections and vaccines to prevent infectious diseases.

Much of infection prevention adopts a one-size-fits-all approach to risk reduction. Many IPC programmes globally implement adaptive strategies considering the scarcity of supporting infrastructure and resource. Precision infection prevention might offer opportunities to tailor IPC measures.[101] In the era of electronic medical records, machine learning can efficiently identify demographic data, select laboratory values, diagnoses, medications, and vital signs, which can then assist to prioritise IPC interventions for patients at greatest risk of an HAI.[102,103] Recognising that much of health care is delivered in environments without experts in infectious diseases, antimicrobial stewardship, microbiology, and infection prevention, virtual infection prevention platforms could be leveraged to assist rural environments and low-resource settings through real-time, expert consultation.[104] Successful models exist for the community expansion of health-care epidemiology programmes.[105] In the innovative and expansive spirit of Pasteur, the collaborative effort engaged through the One Health approach might minimise excessive antimicrobial consumption, and preserve agents for looming threats.[106] Multi-level solutions for complex infection prevention challenges will need broad ingenuity and tenacity of the level of Louis Pasteur.

For more on the **Zoe application** see https://health-study.joinzoe.com/data

For more on the **Aarogya Setu application** see https://www.aarogyasetu.gov.in/applink/

> "*Permettez-moi de vous révéler le secret qui m'a conduit à atteindre mon but. Ma force repose uniquement sur ma ténacité.*"
>
> "Let me tell you the secret that has led to my goal. My strength lies solely in my tenacity."
>
> *Louis Pasteur*

Contributors

AH, RA, and GB wrote the first draft. All authors contributed to the thematic literature review and writing.

Declarations of interest

We declare no competing interests.

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