Infection Prevention and Control of Severe Acute Respiratory Syndrome Coronavirus 2 in Health Care Settings

Marisa L. Winkler, MD, PhD[a,b,c,*], David C. Hooper, MD[a,b,c], Erica S. Shenoy, MD, PhD[a,b,c]

KEYWORDS

• SARS-CoV-2 • COVID-19 • Infection prevention and control • Hierarchy of controls • Standard precautions • Transmission-based precautions

KEY POINTS

- Adherence to the Hierarchy of Controls can mitigate the risk of transmission of infectious diseases.
- Nosocomial COVID-19 transmission events often involve multiple lapses in implementation of infection prevention and control.
- Implementation of the Hierarchy of Controls is likely to evolve over the course of the pandemic.

BACKGROUND

Coronaviruses have been known to infect both humans and animals, and most identified human coronaviruses cause mild seasonal respiratory tract infections.[1] Before the current COVID-19 pandemic caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the outbreaks of severe acute respiratory syndrome coronavirus in 2003 to 2004 and of middle east respiratory syndrome coronavirus in 2012 raised concerns regarding the public health implications of coronaviruses emerging from animals to infect humans.[2,3]

[a] Infection Control Unit, Massachusetts General Hospital, 55 Fruit Street, Bulfinch 334, Boston, MA 02114, USA; [b] Division of Infectious Diseases, Massachusetts General Hospital, 55 Fruit Street, Boston, MA, 02114, USA; [c] Harvard Medical School, 25 Shattuck Street, Boston, MA, 02115, USA

* Corresponding author. Massachusetts General Hospital, 55 Fruit Street, Bulfinch 334, Boston, MA, 02114

E-mail address: mlwinkler@partners.org

Infect Dis Clin N Am 36 (2022) 309–326
https://doi.org/10.1016/j.idc.2022.01.001
id.theclinics.com
0891-5520/22/

This article reviews the chain of transmission of infectious agents, including SARS-CoV-2, recommended infection prevention and control (IPC) practices to mitigate the risk of transmission of SARS-CoV-2 in health care settings, including implementation of the Hierarchy of Controls and evaluation and management of potential nosocomial transmission events, and summarizes lessons learned from transmission events in health care settings.

TRANSMISSION OF INFECTIOUS AGENTS

The chain of transmission of an infectious agent is a cycle comprising multiple parts (**Fig. 1**), and including 3 main requirements: a reservoir of infectious agent, a mode of transmission, and a susceptible host.[4] Reservoirs include humans, animals, and inanimate objects. The infectious agent exits the reservoir and is transmitted by direct or indirect contact (ie, fomite), droplet, or airborne transmission, or a combination of modes. A susceptible host with a portal of entry through which the infectious agent can enter at an inoculum sufficient to result in infection is required to complete the chain of transmission. This involves a complicated interplay of host factors, including vaccination status and response to vaccination for vaccine-preventable diseases,

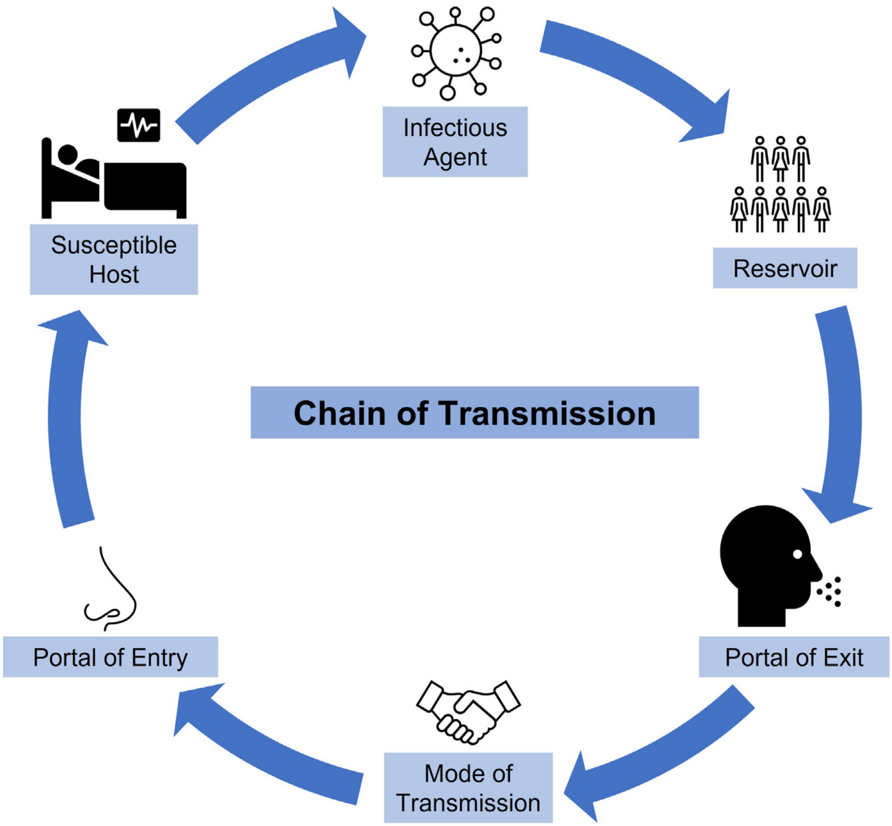

Fig. 1. Chain of transmission: An infectious agent originates from a reservoir where it leaves by a portal of exit, then through a mode of transmission uses a portal of entry in a susceptible host to start a new cycle of infection.

history of prior infection, genetic makeup, and predisposing or immunocompromising conditions.[5,6] One important concept of the chain of transmission is that if any single link in the chain is broken, transmission can be prevented. Interventions within IPC are aimed at multiple links in the chain, providing redundancy, which increases the likelihood of interrupting transmission.

Individuals infected with SARS-CoV-2 can transmit infection while asymptomatic, presymptomatic, and symptomatic. The highest risk of transmission occurs early in infection, before symptom development and within the first 5 days of symptoms, when viral load is highest.[7] Most of the transmission is thought to occur through either deposition of droplet particles on mucous membrane surfaces or inhalation of particles, both in close proximity to the source. Fomite transmission is possible, although not thought to represent a major transmission risk.[8] Despite the ability to culture SARS-CoV-2 from surfaces, the viral particles are easily inactivated by heat or various disinfectants.[9] Proximity of both space and time is a key factor in transmission risk.[9,10] This risk has been demonstrated in studies assessing secondary attack rates, with households reported to have the highest risk, ranging from 17% to 53%.[11–13]

PREVENTION OF TRANSMISSION IN HEALTH CARE SETTINGS: IMPLEMENTATION OF THE HIERARCHY OF CONTROLS

Prevention of transmission in health care settings is focused on breaking links in the chain of transmission, using a layered mitigation approach, often described as the Hierarchy of Controls. This framework was developed by the National Institute of Occupational Safety and Health (NIOSH) to describe interventions to improve workplace safety by reducing workplace hazard risk.[14,15] This framework has been applied to a variety of workplace settings, including health care, during the pandemic to prevent risk of exposure to SARS-CoV-2 (ie, the "hazard"), to health care providers (HCP), patients, and visitors. The framework includes elimination, substitution, engineering controls, administrative controls, and use of personal protective equipment (PPE), in descending order (**Fig. 2**).[14] Generally, interventions at the top of the pyramid are thought to be most effective, and implementation of each level of the pyramid leads to progressively safer environments.

ELIMINATION

During the COVID-19 pandemic, several elimination strategies have been implemented to reduce risk of transmission, including visitor restrictions and use of telemedicine and telework.[16,17] At peak periods of the pandemic, nonessential and elective procedures were canceled, and routine visits were postponed, reducing density in the workplace and clinical areas and also helping manage the volume of patients related to the surge of COVID-related illness. With the first Emergency Use Authorization of COVID-19 vaccines in December 2020, vaccination was added as an elimination strategy. Many employers, including health care facilities, have made employee vaccination for COVID-19 a condition of employment, an approach that has been supported by multiple professional societies and organizations.[18–20] As variants of SARS-CoV-2 evolve, the need for booster vaccinations is likely to be reevaluated, and the definition of full vaccination may change.

Some elimination strategies, notably visitor restrictions, have been associated with negative impacts on patient, HCP, and family well-being in terms of social isolation, reduced quality of life, emotional distress, and difficulty with end-of-life care and have been reconsidered since the initial phase of the pandemic.[21,22] Before the COVID-19 pandemic, studies showed that allowance of visitors did not increase risk

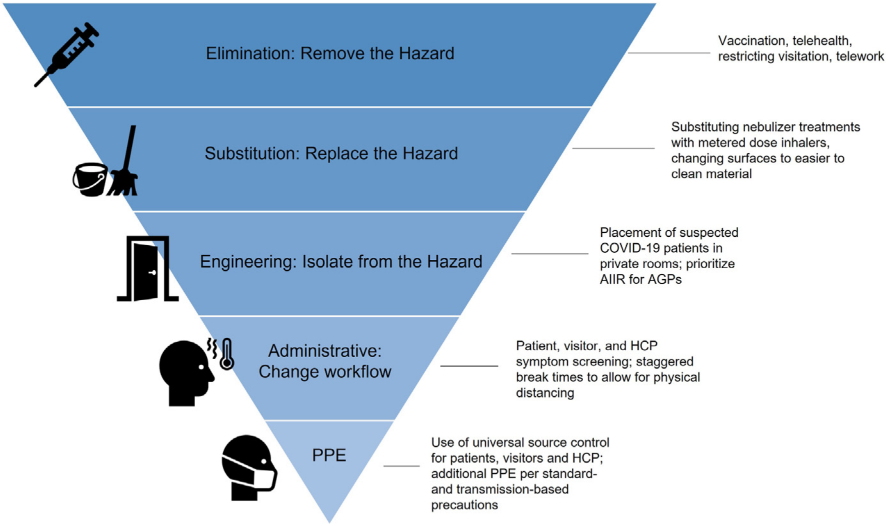

Fig. 2. Following this Hierarchy of Controls normally leads to the implementation of inherently safer systems, where the risk of illness or injury has been substantially reduced. (*Adapted from* Centers for Disease Control and National Institute for Occupational Safety, The National Institute for Occupational Safety and Health (NIOSH): Hierarchy of Controls. Accessed 9/8/2021, https://www.cdc.gov/niosh/topics/hierarchy/default.html)

of infection but did reduce frequency of delirium and anxiety-related symptoms in patients and family satisfaction.[23] The postponement of routine or emergency medical care has led to delayed diagnoses of malignancies and avoidable and ongoing excess morbidity and mortality.[24–26] Although telemedicine can improve access to medical services, it has been found to be less accessible to patients with certain social determinant factors, such as lower income, lower education level, and public insurance.[27,28]

SUBSTITUTION

An example of substitution or replacement of a hazard was a change of nebulizers to metered inhalers, which do not aerosolize secretions and therefore reduce the risk of SARS-CoV-2 transmission.[29,30] Replacing work surfaces with materials that are easier to clean and disinfect is also performed.[31]

ENGINEERING CONTROLS

A variety of engineering controls have been recommended to decrease the risk of SARS-CoV-2 transmission in health care settings. Placement of patients with suspected or confirmed COVID-19, or confirmed exposure during the quarantine period, should be in a standard patient room with the door closed; this room should have a private bathroom.[32] Airborne infection isolation rooms ("negative pressure") are reserved for patients in whom aerosol-generating procedures (AGPs) are anticipated or planned.[32] Patients with confirmed COVID-19 can be grouped together. Appropriate ventilation, filtration, and pressurization of patient care spaces as required by the Facilities Guidelines Institute and public health authorities are essential to prevent infection, reduce contamination, and decrease the number of infectious particles through a combination of air exchanges, occupancy, and cycling time between patient use.[33,34] Eating spaces that allow increased distance between persons were also designed to decrease transmission between employees in the setting of face mask removal.[35]

Administrative Controls

Administrative controls that require changes in workflows constitute a major component of the Hierarchy of Controls. These controls can be some of the most challenging to implement because of their impact on health care operations. Symptom and exposure screening of all HCP, patients, and visitors is recommended. In one study, a sensitivity of 83% was found if at least 2 symptoms of fever, cough, anosmia, dyspnea, oxygen saturation less than 93%, or headache were reported among patients presenting to the emergency department between April and July of 2020.[36] Temperature checks are not a reliable screening tool, as only 19.4% of patients with active COVID-19 infection by polymerase chain reaction (PCR)-based testing platform had a fever $\geq$38°C.[36,37] Other workflow modifications include bundling of clinical tasks to reduce room entry and exit in caring for patients exposed to or with suspected or confirmed COVID-19, enhanced training for clinicians in correct donning and doffing of PPE, and supporting physical distancing when source control (ie, face masks) are removed during break and mealtimes by scheduling staff in a staggered fashion.[35,38,39] An observational study found that restructuring computer workstations, workrooms, break rooms, use of clear cognitive aids, adjusting shift times, and using virtual conferencing are successful in encouraging physical distancing in health care facilities.[35]

Symptom and exposure screening will fail to identify all infected patients, and thus in addition to testing of all symptomatic and exposed patients for COVID-19, asymptomatic testing has been used in specific situations to further reduce the risk of transmission in health care facilities from an occultly infected patient. For patients admitted to facilities or undergoing AGPs, preadmission and preprocedural testing to identify asymptomatic infected individuals has been implemented.[40] Some institutions have instituted surveillance testing at intervals to identify individuals who test negative at admission but may be in the incubation period.[40] In health care facilities with congregate living arrangements as well as behavioral health treatment facilities where physical distancing and compliance with source control may be suboptimal, more frequent asymptomatic screening may be used particularly in the setting of high community prevalence.[40] The conversion rate from negative to positive with serial testing of inpatients was 1% to 1.9% in 2 studies.[41,42] Specific screening strategies are expected to change over time, based on a combination of factors, including community prevalence and vaccination within the specific community and patient population.

High rates of presenteeism (HCP working while sick) have been documented with symptom monitoring and remains a challenge.[43] Early reports during the COVID-19 pandemic found that 64.6% of infected HCP came to work after developing symptoms.[44] Use of a passive symptom screening tool found that 82% of those who screened positive had not been planning to stay home from work.[43]

HCP should similarly be evaluated if they develop symptoms consistent with COVID-19 or have a confirmed exposure. The role of routine testing of asymptomatic HCP has not been demonstrated to be necessary to support IPC when strategies are in place to limit risk of transmission. Several studies have demonstrated the prevalence of asymptomatic infection in HCP to be less than 1% in 2020.[45] Mass testing of asymptomatic HCP in 1 facility found 15 asymptomatic HCP who tested positive out of 13,703 total tests, with a much lower prevalence of positive results compared with the community.[46] Current Centers for Disease Control and Prevention (CDC) guidance states that testing with either a PCR- or antigen-based test should be performed in the setting of symptoms and can be considered in asymptomatic HCP if community risk and transmission levels are high.[40] As with testing strategies for patients, strategies applied to HCP are expected to change over time, based on the same factors of community prevalence and vaccination among HCP and the community.

PERSONAL PROTECTIVE EQUIPMENT

The final component of the Hierarchy of Controls is the use of PPE. Although correct and consistent use of PPE is a cornerstone of HCP and patient safety, it appears at the bottom of the pyramid, as it is susceptible to human error and requires compliance.[15] In the setting of the COVID-19 pandemic, universal source control (ie, use of a face mask for HCP, patients, and visitors) has been implemented and associated with reduced risk of transmission.[47–51] In addition, use of eye protection (ie, face shields or goggles) is recommended for use by HCP in all clinical encounters during periods of substantial to high community transmission as a barrier to prevent direct mucous membrane inoculation and contamination of the eyes by hands.[52] Patients with suspected or confirmed COVID-19, or confirmed exposures to COVID-19 in the quarantine period, are managed in health care settings using Standard and Transmission-based precautions.[32,53] For these patients, the recommended PPE by the CDC includes an NIOSH-approved fit-tested N95 filtering facepiece respirator or higher, eye protection (face shield or goggles), gown, and gloves. Personal glasses are not considered to be sufficient protective eyewear.[54] Both the CDC and World Health Organization (WHO) state that in the setting of N95 respirator shortages, face masks can be used for patient care outside of AGPs.[55]

The CDC definition of AGP includes suctioning of airways, sputum induction, cardiopulmonary resuscitation, endotracheal intubation and extubation, noninvasive ventilation, bronchoscopy, manual ventilation, nebulizer administration, high-flow oxygen delivery, or procedures involving areas of higher viral load, such as nose and throat, oropharynx, or respiratory tract.[32,56] WHO definition of AGP includes tracheal intubation, noninvasive ventilation, tracheostomy, cardiopulmonary resuscitation, manual ventilation, bronchoscopy, sputum induction using nebulized hypertonic saline, dentistry, and autopsy procedures.[57,58] The definition of an AGP has evolved during the pandemic, and analysis has found that the patient characteristics, such as severe illness with high viral load and significant symptoms, sustained exposure by HCP to the patient, and procedures with close proximity to the respiratory tract are more significant factors leading to transmission events.[59]

Practice in use of face masks or N95 respirators for care of patients with suspected or confirmed COVID-19 or confirmed exposures outside of AGPs has varied; in 1 survey of Veterans Administration facilities, 63% used N95 respirators in all patients with suspected or confirmed COVID-19.[60] A meta-analysis of randomized trials did not find a statistical difference in the risk of acquiring a respiratory infection when wearing a surgical mask or an N95 respirator.[61]

Early in the COVID-19 pandemic, owing to disruption in the supply chain of PPE, crisis and contingency standards of care were implemented under guidance from public health authorities.[62,63] Reuse of PPE, defined as donning for a patient contact then doffing and storing for use with another patient, and extended use, defined as wearing PPE for a prolonged period, including multiple patient contacts before removing and discarding, were used for items that under conventional standards are single use.[62] The implementation of extended use and reuse raises challenges related to the potential for cross- and self-contamination as well as concerns for decrements in filtration efficiency and fit over multiple uses of N95 respirators.[64,65] Supplies have improved over the course of the pandemic, and many health care settings have returned to conventional standards in the use of PPE.[66] The impact of extended use and reuse on effectiveness of PPE has been assessed without failure over up to 12 reuses,[67] but concerns have been raised regarding failure with higher numbers of reuse.[67–69] There is also concern regarding contamination of PPE over multiple uses even in the setting of proper handling technique.[65] Simulation training to increase the understanding of infection control practices in the setting of donning or doffing PPE, resuscitation, airway management, and transportation was performed in some hospitals.[70–72] Some facilities have provided just-in-time education with observed donning and doffing to improve HCP practice.[70]

EVALUATION AND MANAGEMENT OF HEALTH CARE PROVIDER INFECTIONS AND EXPOSURES

Infections in HCP risk spread to other HCP, patients, and visitors. Contact tracing of HCP with infections is important to determine, when possible, the likely source of infection, if breaches in correct practices may have contributed, and to identify potentially exposed HCP, patients, and others. Studies have shown that most HCP infections are attributable to community exposures and not related to occupational exposure, particularly in the setting of appropriate IPC procedures.[73]

Duration of isolation for infected HCP and duration of quarantine for exposed HCP continue to evolve. HCP who are moderately to severely immunocompromised or with severe illness may require either longer duration of isolation when infected or a test-based approach to clearance with consultation with both local infectious disease and occupational health experts.

Exposure definitions in health care differ in important ways with respect to mitigating risk of exposure through use of PPE. In health care settings, exposures that qualify based on duration (cumulative 15 minutes of direct contact) and proximity (within 6 feet) can be mitigated by use of PPE.[74] In the setting of an AGP, if proper PPE is not worn, then an exposure is considered to have occurred regardless of the duration of interaction. The CDC framework for managing HCP exposures is detailed, including vaccination status, postexposure testing, level of staffing, and restrictions from work. Lack of eye protection has been associated with COVID-19 infection following occupational exposure.[52,75,76] Despite implementation of multiple infection prevention interventions, transmission in health care settings has been observed, although it is low in the setting of adherence to IPC methods.[77]

HCP are expected to report community exposures to their occupational health departments to determine the testing protocol and work restriction, and frequently household exposures are managed in a similar manner as high-risk occupational exposures.[74]

TRANSMISSION IN HEALTH CARE SETTINGS AND LESSONS LEARNED

The potential routes of transmission in health care settings include patient-to-HCP, patient-to-patient, HCP-to-HCP, HCP-to-patient, visitor-to-patient, and visitor-to-HCP. Examples of each are discussed later and described in **Table 1**. For the most part, the published exposure and transmission events described occurred before widespread vaccination of HCP and the general public. Transmission has, however, been noted in health care settings in the postvaccination period. Common themes

Table 1
Documented health care facility severe acute respiratory syndrome coronavirus 2 outbreaks, actions attributed to the spread of infection, and facility response to contain infections

Outbreak Setting	Number of Infected People	Attributable Actions	Response to Infection	Citation
Long-term care facilities, skilled nursing facilities, or nursing homes				
Skilled nursing facility	16 HCP, 5 residents	Presenteeism	Closure to new admissions, limited ancillary services, contact tracing, symptom screening, serial respiratory surveys, whole genome sequencing to characterize spread, isolate staff with close contact with confirmed cases, restrict movement between units, uniform masking, use of recommended PPE (isolation gown, N95 respirator, gloves, and eye protection with face shield or reusable goggles) for interactions in units with cases, training for donning and doffing, hand hygiene, and cleaning	[93]
Ambulatory (including emergency department)				
Emergency department	2 clusters, one with 3 HCP, one with 2 HCP	Close interactions among coworkers without source control	Reinforced uniform masking, increased space between computer workstations, encouraged social distancing and avoiding shared meals	[88]
Inpatient				
Inpatient stroke ward	14 HCP and 10 patients	Patients moving through ward unmasked, close contact	Increased PPE, quarantined exposed patients, decreased	[94]

		required between patients and staff, decreased compliance with hand hygiene	break room capacity, increased random PPE and cleaning assessments, HCP offered testing	
Academic cancer center	3 clusters, first with 8 HCP, second with 4 HCP, third with 2 HCP	Presenteeism	Reinforcement of symptom reporting, enhanced cleaning, reinforcement and monitoring of masking, break room closed and gathering prohibited, isolation of all positive HCP, testing of all asymptomatic employees in same area	89
Inpatient medical ward	3 HCP	Undiagnosed patient receiving AGPs without appropriate precautions	Early testing and isolation of patients with possible COVID-19, use of eye protection, gowns, N95 respirators, or powered air-purifying respirators in the setting of AGPs	79
Inpatient psychiatry unit	5 HCP and 5 patients	Community-exposed patient with minimal symptoms admitted to double room, slow uptake of PPE by staff, patient behaviors limited appropriate PPE use, physical distancing difficult given need for group sessions and meals, limited testing capacity early in pandemic	Closed to new admissions, universal PPE, observed hand hygiene before meals and group therapy, restricted visitors, staff and patient symptom screening, limited number of patients in shared spaces by staggered group mealtimes, increased cleaning frequency	80
OR staff	24 HCP	Presenteeism, using communal spaces, including break rooms, without appropriate IC practices, other nonoccupational high-risk exposure	Increased cleaning, rapid screening of asymptomatic HCP, reeducation regarding masking, limiting capacity in communal areas, quarantine if symptomatic	95

(*continued on next page*)

Table 1
(*continued*)

Outbreak Setting	Number of Infected People	Attributable Actions	Response to Infection	Citation
Integrated health care system	14 (not separated between HCP and patients)	Presenteeism, transport of infectious patients between facilities, no universal masking or use of PPE, no available in-house testing, patients not under isolation while testing pending, shared rooms, variable symptom screening	Implemented universal source control, symptom screening at facility entrance, empiric precautions until test results if patients screen positive for symptoms, restricted visitors, altered testing algorithm, testing all new admissions	81
Acute care hospital	38 HCP, 14 patients	Symptomatic patient with false-negative serial testing receiving AGPs, shared rooms, infectious patients moved several times, positive pressure in index patient room, lack of eye protection among staff, interaction among unmasked staff in nonclinical areas	Mobilized incident command for cluster response, increased testing capacity, serial testing of all patients and exposed staff, preemptive enhanced respiratory isolation for all patients on involved units, positive patients moved to dedicated unit, enhanced cleaning of affected units, occupational health interviews of all positive staff, air changes and airflow patterns assessed	75

Abbreviations: ERI, enhanced respiratory isolation; HCP, healthcare provider, PPE, personal protective equipment, AGP, aerosol-generating procedure, OR, operating room, IC, infection control.

from nosocomial transmission events include HCP presenteeism, lack of compliance with IPC measures including appropriate use of PPE, and unrecognized asymptomatic, presymptomatic, or symptomatic infection in patients who subsequently undergo high-risk activities, such as AGPs.

Despite symptom screening of patients and the use of testing to identify asymptomatic infection, patients who are incubating infection on admission and are missed by such strategies, or patients who acquire infection from another source (roommate, HCP, visitor) during the course of an admission while not isolated, can result in exposures to HCP and other patients.[75,78–81] In one outbreak in an acute care hospital, tracing by epidemiology and genomic sequencing found late-onset infection following admission of the index patient who spread COVID-19 to both other patients and HCP.[75] The initial exposure event was attributed to a symptomatic patient who tested negative for SARS-CoV-2 on 2 serial nasopharyngeal swabs upon admission with subsequent AGPs performed. At the time of the cluster, universal source control with face masks was in place for all HCP and eye protection for all interactions with patients. In response to this cluster, implementation of serial admission screening as well as repeat screening before AGPs was implemented. Studies show an attack rate of 0% to 4.7% for hospital exposures versus 15.2% for community exposures, supporting the efficacy of layered infection control approaches to reduce risk of transmission, including universal source control.[82–84]

Patient-to-patient transmission in the setting of roommates in semiprivate accommodations in health care facilities has been directly studied.[85,86] In one report over 7 months at an acute care hospital, there were 31 exposed patient roommates, 39% of whom ultimately tested positive for SARS-CoV-2.[85] The beds were 5 feet apart side by side and 7 feet apart mid-pillow to mid-pillow with a closed curtain between them. Exposed patients who subsequently became infected were more likely to have roommates with cycle thresholds $\leq$ 21 by PCR-based testing. A separate study found a secondary attack rate for hospitalized roommates of 18.9% overall and 35.7% in the setting of AGPs.[86] The attack rate in these scenarios mirrors that observed in household settings.[11–13,87] Infections among patients have also been observed in inpatient psychiatric units where it is difficult to promote mask wearing, distancing, and hand hygiene, and group activities are instrumental to treatment.[80] Strategies to reduce the risk of patient-to-patient transmission include serial testing at regular intervals during hospitalization and rapid isolation with positive testing or development of symptoms.

Multiple descriptions of transmission events between HCP resulting in clusters of infections have been reported in the literature. Often the initial source is attributed to community acquisition with subsequent occupational spread in break rooms or other settings where masks are removed and where distance is not maintained. Presenteeism has been featured in several published accounts.[43,44,88,89] Since the widespread adoption of vaccination against SARS-CoV-2, in areas with minimal community transmission, current CDC guidance permits fully vaccinated HCP to be nonmasked and nondistanced for dining or socializing in areas restricted from patient access.[32] However, as evidence of postvaccination infection increases, guidelines regarding this are also evolving.[90,91]

Exposures from infected HCP to patients resulting in transmission appear to be uncommon, especially in the era of universal masking in health care facilities. A study evaluating transmission from infected HCP to patients found 2 transmission events, one where neither the HCP nor patient was wearing a mask and one where the patient was not wearing a mask but also had a household exposure.[92]

Visitors to health care facilities are screened for symptoms and exposure and are required to wear face masks. Transmission from infected visitors is not thought to be common, although can occur, usually in the setting of lack of masking between visitors and the patients they are visiting. One transmission event from a presymptomatic infected spouse visiting daily to a patient infected on hospital day 15 was reported.[42]

In most nosocomial clusters, there may be multiple events arising from a single index source, before recognition of the transmission events and implementation of additional control measures as appropriate.

SUMMARY

IPC approaches to prevention of SARS-CoV-2 transmission in health care settings are grounded in understanding the chain of transmission and implementation of the Hierarchy of Controls. As community prevalence of SARS-CoV-2 waxes and wanes, duration and protection from vaccines continue to be assessed, and effective and accessible therapies and prophylaxis options emerge, the relative importance of various components of mitigation strategies will change. This will mean that public health recommendations and health care facilities strategies will continue to evolve.

CLINICS CARE POINTS

- Transmission of infectious agents in health care settings can be interrupted through application of the Hierarchy of Controls.
- The Hierarchy of Controls involves elimination, substitution, engineering controls, administrative controls, and use of personal protective equipment; implementation of multiple strategies reduces the risk of transmission.
- Observed transmission events in health care settings often involve multiple lapses in control measures, including health care personnel presenteeism, lack of compliance with infection prevention and control measures, and unrecognized infections in patients.

ACKNOWLEDGMENTS

The authors thank Noah Feder for assistance with figure preparation. We would also like to thank Massachusetts General Hospital for support of the Infection Prevention, Healthcare Epidemiology, and Antimicrobial Stewardship training track.

DISCLOSURE

None.

REFERENCES

1. V'Kovski P, Kratzel A, Steiner S, et al. Coronavirus biology and replication: implications for SARS-CoV-2. Nat Rev Microbiol 2021;19(3):155–70.
2. Cui J, Li F, Shi ZL. Origin and evolution of pathogenic coronaviruses. Nat Rev Microbiol 2019;17(3):181–92.
3. Hu B, Guo H, Zhou P, et al. Characteristics of SARS-CoV-2 and COVID-19. Nat Rev Microbiol 2021;19(3):141–54.
4. Dicker RC, Coronado F, Koo D, et al. Principles of epidemiology in public health practice, 3rd edition. An introduction to applied epidemiology and biostatistics, lesson 1: introduction to epidemiology. Section 10: CHAIN OF INfection. Available

at: https://www.cdc.gov/csels/dsepd/ss1978/lesson1/section10.html. Accessed October 25, 2021.
5. Fricke-Galindo I, Falfan-Valencia R. Genetics Insight for COVID-19 susceptibility and severity: a review. Front Immunol 2021;12:622176.
6. Liu X, Zhou H, Zhou Y, et al. Risk factors associated with disease severity and length of hospital stay in COVID-19 patients. J Infect 2020;81(1):e95–7.
7. Delta variant: what we know about the science. Available at: https://www.cdc.gov/coronavirus/2019-ncov/variants/delta-variant.html. Accessed September 6, 2021.
8. Science brief: SARS-CoV-2 and surface (fomite) transmission for indoor community environments. Available at: https://www.cdc.gov/coronavirus/2019-ncov/more/science-and-research/surface-transmission.html. Accessed October 18, 2021.
9. Meyerowitz EA, Richterman A, Gandhi RT, et al. Transmission of SARS-CoV-2: a review of viral, host, and environmental factors. Ann Intern Med 2021;174(1):69–79.
10. Transmission of SARS-CoV-2: implications for infection prevention precautions. Available at: https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions. Accessed September 6, 2021.
11. Martinez DA, Klein EY, Parent C, et al. Latino household transmission of SARS-CoV-2. Clin Infect Dis 2021. https://doi.org/10.1093/cid/ciab753.
12. Musa S, Kissling E, Valenciano M, et al. Household transmission of SARS-CoV-2: a prospective observational study in Bosnia and Herzegovina, August - December 2020. Int J Infect Dis 2021. https://doi.org/10.1016/j.ijid.2021.09.063.
13. Grijalva CG, Rolfes MA, Zhu Y, et al. Transmission of SARS-COV-2 Infections in Households - Tennessee and Wisconsin, April-September 2020. MMWR Morb Mortal Wkly Rep 2020;69(44):1631–4.
14. The National Institute for Occupational Safety and Health (NIOSH): hierarchy of controls. Available at: https://www.cdc.gov/niosh/topics/hierarchy/default.html. Accessed September 8, 2021.
15. Kraus A, Awoniyi O, AlMalki Y, et al. Practical solutions for healthcare worker protection during the COVID-19 pandemic response in the ambulatory, emergency, and inpatient settings. J Occup Environ Med 2020;62(11):e616–24.
16. Using telehealth to expand access to essential health services during the COVID-19 pandemic. Available at: https://www.cdc.gov/coronavirus/2019-ncov/hcp/telehealth.html. Accessed September 17, 2021.
17. Bashshur R, Doarn CR, Frenk JM, et al. Telemedicine and the COVID-19 pandemic, lessons for the future. Telemed J E Health 2020;26(5):571–3.
18. Weber DJ, Al-Tawfiq JA, Babcock HM, et al. Multisociety statement on coronavirus disease 2019 (COVID-19) vaccination as a condition of employment for healthcare personnel. Infect Control Hosp Epidemiol 2021;1–9. https://doi.org/10.1017/ice.2021.322.
19. Joint statement in support of COVID-19 vaccine mandates for all workers in health and long-term care. Available at: https://www.acponline.org/acp_policy/statements/joint_statement_covid_vaccine_mandate_2021.pdf. Accessed October 16, 2021.
20. AHA Policy Statement on mandatory COVID-19 vaccination of health care personnel. Available at: https://www.aha.org/public-comments/2021-07-21-aha-policy-statement-mandatory-covid-19-vaccination-health-care. Accessed October 16, 2021.

21. Wendlandt B, Kime M, Carson S. The impact of family visitor restrictions on healthcare workers in the ICU during the COVID-19 pandemic. Intensive Crit Care Nurs 2021;103123. https://doi.org/10.1016/j.iccn.2021.103123.
22. Hindmarch W, McGhan G, Flemons K, et al. COVID-19 and long-term care: the essential role of family caregivers. Can Geriatr J 2021;24(3):195–9.
23. Nassar Junior AP, Besen B, Robinson CC, et al. Flexible versus restrictive visiting policies in ICUs: a systematic review and meta-analysis. Crit Care Med 2018;46(7):1175–80.
24. Excess deaths associated with COVID-19. Available at: https://www.cdc.gov/nchs/nvss/vsrr/covid19/excess_deaths.htm. Accessed September 17, 2021.
25. Czeisler ME, Marynak K, Clarke KEN, et al. Delay or avoidance of medical care because of COVID-19-related concerns - United States, June 2020. MMWR Morb Mortal Wkly Rep 2020;69(36):1250–7.
26. Woolf SH, Chapman DA, Sabo RT, et al. Excess deaths from COVID-19 and other causes in the US, March 1, 2020, to January 2, 2021. JAMA 2021. https://doi.org/10.1001/jama.2021.5199.
27. Luo J, Tong L, Crotty BH, et al. Telemedicine adoption during the COVID-19 pandemic: gaps and inequalities. Appl Clin Inform Aug 2021;12(4):836–44.
28. Sun R, Blayney DW, Hernandez-Boussard T. Health management via telemedicine: learning from the COVID-19 experience. J Am Med Inform Assoc 2021. https://doi.org/10.1093/jamia/ocab145.
29. Amirav I, Newhouse MT. COVID-19: time to embrace MDI+ valved-holding chambers. J Allergy Clin Immunol 2020;146(2):331.
30. Sethi S, Barjaktarevic IZ, Tashkin DP. The use of nebulized pharmacotherapies during the COVID-19 pandemic. Ther Adv Respir Dis 2020;14. https://doi.org/10.1177/1753466620954366. 1753466620954366.
31. Background E. Environmental services. Available at: https://www.cdc.gov/infectioncontrol/guidelines/environmental/background/services.html. Accessed October 29, 2021.
32. Interim infection prevention and control recommendations for healthcare personnel during the coronavirus disease 2019 (COVID-19) pandemic. Available at: https://www.cdc.gov/coronavirus/2019-ncov/hcp/infection-control-recommendations.html. Accessed October 19, 2021.
33. Heating, ventilation, and air conditioning systems in health-care facilities. Available at: https://www.cdc.gov/infectioncontrol/guidelines/environmental/background/air.html#c3. Accessed October 16, 2021.
34. Filtration/disinfection. Available at: https://www.ashrae.org/technical-resources/filtration-disinfection#mechanical. Accessed October 16, 2021.
35. Keller SC, Pau S, Salinas AB, et al. Barriers to physical distancing among healthcare workers on an academic hospital unit during the coronavirus disease 2019 (COVID-19) pandemic. Infect Control Hosp Epidemiol 2021;1–7. https://doi.org/10.1017/ice.2021.154.
36. Romero-Gameros CA, Colin-Martinez T, Waizel-Haiat S, et al. Diagnostic accuracy of symptoms as a diagnostic tool for SARS-CoV 2 infection: a cross-sectional study in a cohort of 2,173 patients. BMC Infect Dis 2021;21(1):255.
37. Vilke GM, Brennan JJ, Cronin AO, et al. Clinical features of patients with COVID-19: is temperature screening useful? J Emerg Med 2020;59(6):952–6.
38. Amer HA, Alowidah IA, Bugtai C, et al. Challenges to infection control team during COVID-19 pandemic in a quaternary medical center in Saudi Arabia. Infect Control Hosp Epidemiol 2021;1–20. https://doi.org/10.1017/ice.2021.72.

39. Zhang H, Dimitrov D, Simpson L, et al. A web-based, mobile-responsive application to screen health care workers for COVID-19 symptoms: rapid design, deployment, and usage. JMIR Form Res 2020;4(10):e19533.
40. Overview of testing for SARS-CoV-2 (COVID-19). Available at: https://www.cdc.gov/coronavirus/2019-ncov/hcp/testing-overview.html. Accessed October 19, 2021.
41. Kobayashi T, Trannel A, Holley SA, et al. COVID-19 serial testing among hospitalized patients in a midwest tertiary medical center, July-September 2020. Clin Infect Dis 2020. https://doi.org/10.1093/cid/ciaa1630.
42. Rhee C, Baker M, Vaidya V, et al. Incidence of nosocomial COVID-19 in patients hospitalized at a large US academic medical center. JAMA Netw Open 2020;3(9):e2020498.
43. Lichtman A, Greenblatt E, Malenfant J, et al. Universal symptom monitoring to address presenteeism in healthcare workers. Am J Infect Control 2021;49(8):1021–3.
44. Chow EJ, Schwartz NG, Tobolowsky FA, et al. Symptom screening at illness onset of health care personnel with SARS-CoV-2 infection in King County, Washington. JAMA 2020;323(20):2087–9.
45. Chow A, Htun HL, Kyaw WM, et al. Asymptomatic health-care worker screening during the COVID-19 pandemic. Lancet 2020;396(10260):1393–4.
46. Roberts SC, Peaper DR, Thorne CD, et al. Mass severe acute respiratory coronavirus 2 (SARS-CoV-2) testing of asymptomatic healthcare personnel. Infect Control Hosp Epidemiol 2021;42(5):625–6.
47. Klompas M, Morris CA, Sinclair J, et al. Universal masking in hospitals in the Covid-19 era. N Engl J Med 2020;382(21):e63.
48. Leung NHL, Chu DKW, Shiu EYC, et al. Respiratory virus shedding in exhaled breath and efficacy of face masks. Nat Med 2020;26(5):676–80.
49. Walker J, Fleece ME, Griffin RL, et al. Decreasing high-risk exposures for healthcare workers through universal masking and universal SARS-CoV-2 testing upon entry to a tertiary care facility. Clin Infect Dis 2020. https://doi.org/10.1093/cid/ciaa1358.
50. Wang X, Ferro EG, Zhou G, et al. Association between universal masking in a health care system and SARS-CoV-2 positivity among health care workers. JAMA 2020;324(7):703–4.
51. Seidelman JL, Lewis SS, Advani SD, et al. Universal masking is an effective strategy to flatten the severe acute respiratory coronavirus virus 2 (SARS-CoV-2) healthcare worker epidemiologic curve. Infect Control Hosp Epidemiol 2020;41(12):1466–7.
52. Chu DK, Akl EA, Duda S, et al. Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. Lancet 2020;395(10242):1973–87.
53. Core infection prevention and control practices for safe healthcare delivery in all settings –recommendations of the HICPAC. Available at: https://www.cdc.gov/hicpac/recommendations/core-practices.html. Accessed September 17, 2021.
54. The National Institute for Occupational Safety and Health (NIOSH): eye safety. Available at: https://www.cdc.gov/niosh/topics/eye/eye-infectious.html. Accessed October 10, 2021.
55. Mask use in the context of COVID-19. Available at: https://apps.who.int/iris/bitstream/handle/10665/337199/WHO-2019-nCov-IPC_Masks-2020.5-eng.pdf?sequence=1&isAllowed=y. Accessed October 14, 2021.

56. Tran K, Cimon K, Severn M, et al. Aerosol generating procedures and risk of transmission of acute respiratory infections to healthcare workers: a systematic review. PLoS One 2012;7(4):e35797.
57. Mask use in the context of COVID-19. Available at: https://www.who.int/publications/i/item/advice-on-the-use-of-masks-in-the-community-during-home-care-and-in-healthcare-settings-in-the-context-of-the-novel-coronavirus-(2019-ncov)-outbreak. Accessed October 22, 2021.
58. Mask use in the context of COVID-19. Available at: https://www.who.int/publications/i/item/advice-on-the-use-of-masks-in-the-community-during-home-care-and-in-healthcare-settings-in-the-context-of-the-novel-coronavirus-(2019-ncov)-outbreak. Accessed October 29, 2021.
59. Klompas M, Baker M, Rhee C. What is an aerosol-generating procedure? JAMA Surg 2021;156(2):113–4.
60. McCormick WL, Koster MP, Sood GN, et al. Level of respiratory protection for healthcare workers caring for coronavirus disease 2019 (COVID-19) patients: a survey of hospital epidemiologists. Infect Control Hosp Epidemiol 2021;1–2. https://doi.org/10.1017/ice.2021.74.
61. Barycka K, Szarpak L, Filipiak KJ, et al. Comparative effectiveness of N95 respirators and surgical/face masks in preventing airborne infections in the era of SARS-CoV2 pandemic: a meta-analysis of randomized trials. PLoS One 2020;15(12):e0242901.
62. Implementing Filtering Facepiece Respirator (FFR) reuse, including reuse after decontamination, when there are known shortages of N95 respirators. Available at: https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/decontamination-reuse-respirators.html. Accessed September 17, 2021.
63. Fisher EM, Shaffer RE. Considerations for recommending extended use and limited reuse of filtering facepiece respirators in health care settings. J Occup Environ Hyg 2014;11(8):D115–28.
64. Peters A, Palomo R, Ney H, et al. The COVID-19 pandemic and N95 masks: reusability and decontamination methods. Antimicrob Resist Infect Control 2021;10(1):83.
65. Li DF, Alhmidi H, Scott JG, et al. A simulation study to evaluate contamination during reuse of N95 respirators and effectiveness of interventions to reduce contamination. Infect Control Hosp Epidemiol 2021;1–6. https://doi.org/10.1017/ice.2021.218.
66. FDA recommends transition from use of decontaminated disposable respirators - letter to health care personnel and facilities. Available at: https://www.fda.gov/medical-devices/letters-health-care-providers/fda-recommends-transition-use-decontaminated-disposable-respirators-letter-health-care-personnel-and. Accessed September 17, 2021.
67. Fabre V, Cosgrove SE, Hsu YJ, et al. N95 filtering face piece respirators remain effective after extensive reuse during the coronavirus disease 2019 (COVID-19) pandemic. Infect Control Hosp Epidemiol 2021;42(7):896–9.
68. Degesys NF, Wang RC, Kwan E, et al. Correlation between N95 extended use and reuse and fit failure in an emergency department. JAMA 2020;324(1):94–6.
69. Bergman MS, Viscusi DJ, Zhuang Z, et al. Impact of multiple consecutive donnings on filtering facepiece respirator fit. Am J Infect Control 2012;40(4):375–80.
70. Cheng VC, Wong SC, Tong DW, et al. Multipronged infection control strategy to achieve zero nosocomial coronavirus disease 2019 (COVID-19) cases among Hong Kong healthcare workers in the first 300 days of the pandemic. Infect Control Hosp Epidemiol 2021;1–10. https://doi.org/10.1017/ice.2021.119.

71. COVID-19 simulation exercises packages. Available at: https://www.who.int/emergencies/diseases/novel-coronavirus-2019/training. Accessed September 17, 2021.
72. Pan D, Rajwani K. Implementation of simulation training during the COVID-19 pandemic: a New York Hospital experience. Simul Healthc 2021;16(1):46–51.
73. Team CC-R. Characteristics of health care personnel with COVID-19 - United States, February 12-April 9, 2020. MMWR Morb Mortal Wkly Rep 2020;69(15):477–81.
74. Interim guidance for managing healthcare personnel with SARS-CoV-2 infection or exposure to SARS-CoV-2. Available at: https://www.cdc.gov/coronavirus/2019-ncov/hcp/guidance-risk-assesment-hcp.html. Accessed January 2, 2022.
75. Klompas M, Baker MA, Rhee C, et al. A SARS-CoV-2 cluster in an acute care hospital. Ann Intern Med 2021;174(6):794–802.
76. Shah VP, Breeher LE, Hainy CM, et al. Evaluation of healthcare personnel exposures to patients with severe acute respiratory coronavirus virus 2 (SARS-CoV-2) associated with personal protective equipment. Infect Control Hosp Epidemiol 2021;1–5. https://doi.org/10.1017/ice.2021.219.
77. Habermann EB, Tande AJ, Pollock BD, et al. Providing safe care for patients in the coronavirus disease 2019 (COVID-19) era: a case series evaluating risk for hospital-associated COVID-19. Infect Control Hosp Epidemiol 2021;1–7. https://doi.org/10.1017/ice.2021.38.
78. Saidel-Odes L, Nesher L, Nativ R, et al. An outbreak of coronavirus disease 2019 (COVID-19) in hematology staff via airborne transmission. Infect Control Hosp Epidemiol 2021;1–2. https://doi.org/10.1017/ice.2020.1431.
79. Heinzerling A, Stuckey MJ, Scheuer T, et al. Transmission of COVID-19 to health care personnel during exposures to a hospitalized patient - Solano County, California, February 2020. MMWR Morb Mortal Wkly Rep 2020;69(15):472–6.
80. McGloin JM, Asokaraj N, Feeser B, et al. Coronavirus disease 2019 (COVID-19) outbreak on an inpatient psychiatry unit: Mitigation and prevention. Infect Control Hosp Epidemiol 2021;1–2. https://doi.org/10.1017/ice.2021.233.
81. Thompson ER, Williams FS, Giacin PA, et al. Universal masking to control healthcare-associated transmission of severe acute respiratory coronavirus virus 2 (SARS-CoV-2). Infect Control Hosp Epidemiol 2021;1–7. https://doi.org/10.1017/ice.2021.127.
82. Ng K, Poon BH, Kiat Puar TH, et al. COVID-19 and the risk to health care workers: a case report. Ann Intern Med 2020;172(11):766–7.
83. Baker MA, Rhee C, Fiumara K, et al. COVID-19 infections among HCWs exposed to a patient with a delayed diagnosis of COVID-19. Infect Control Hosp Epidemiol 2020;41(9):1075–6.
84. Howell A, Havens L, Swinford W, et al. PPE effectiveness - yes, the buck and virus can stop here. Infect Control Hosp Epidemiol 2021;1–3. https://doi.org/10.1017/ice.2021.75.
85. Karan A, Klompas M, Tucker R, et al. The risk of SARS-CoV-2 transmission from patients with undiagnosed Covid-19 to roommates in a large academic medical center. Clin Infect Dis 2021. https://doi.org/10.1093/cid/ciab564.
86. Chow K, Aslam A, McClure T, et al. Risk of healthcare-associated transmission of SARS-CoV-2 in hospitalized cancer patients. Clin Infect Dis 2021. https://doi.org/10.1093/cid/ciab670.
87. Lindstrom JC, Engebretsen S, Kristoffersen AB, et al. Increased transmissibility of the alpha SARS-CoV-2 variant: evidence from contact tracing data in Oslo,

January to February 2021. Infect Dis (Lond) 2021;1–6. https://doi.org/10.1080/23744235.2021.1977382.

88. Chan ER, Jones LD, Redmond SN, et al. Use of whole-genome sequencing to investigate a cluster of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infections in emergency department personnel. Infect Control Hosp Epidemiol 2021;1–3. https://doi.org/10.1017/ice.2021.208.
89. Ariza-Heredia EJ, Frenzel E, Cantu S, et al. Surveillance and identification of clusters of healthcare workers with coronavirus disease 2019 (COVID-19): multidimensional interventions at a comprehensive cancer center. Infect Control Hosp Epidemiol 2021;42(7):797–802.
90. Britton A, Jacobs Slifka KM, Edens C, et al. Effectiveness of the Pfizer-BioNTech COVID-19 vaccine among residents of two skilled nursing facilities experiencing COVID-19 outbreaks - Connecticut, December 2020-February 2021. MMWR Morb Mortal Wkly Rep 2021;70(11):396–401.
91. Teran RA, Walblay KA, Shane EL, et al. Postvaccination SARS-CoV-2 infections among skilled nursing facility residents and staff members - Chicago, Illinois, December 2020-March 2021. MMWR Morb Mortal Wkly Rep 2021;70(17):632–8.
92. Baker MA, Fiumara K, Rhee C, et al. Low risk of COVID-19 among patients exposed to infected healthcare workers. Clin Infect Dis 2020. https://doi.org/10.1093/cid/ciaa1269.
93. Karmarkar EN, Blanco I, Amornkul PN, et al. Timely intervention and control of a novel coronavirus (COVID-19) outbreak at a large skilled nursing facility-San Francisco, California, 2020. Infect Control Hosp Epidemiol 2020;1–8. https://doi.org/10.1017/ice.2020.1375.
94. Lesho EP, Walsh EE, Gutowski J, et al. A cluster-control approach to a coronavirus disease 2019 (COVID-19) outbreak on a stroke ward with infection control considerations for dementia and vascular units. Infect Control Hosp Epidemiol 2021;1–7. https://doi.org/10.1017/ice.2020.1437.
95. McDougal AN, Elhassani D, DeMaet MA, et al. Outbreak of coronavirus disease 2019 (COVID-19) among operating room staff of a tertiary referral center: an epidemiologic and environmental investigation. Infect Control Hosp Epidemiol 2021;1–7. https://doi.org/10.1017/ice.2021.116.