

Nosocomial infection of COVID-19: A new challenge for healthcare professionals (Review)

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Abstract. Nosocomial infections, also known as hospital-acquired infections, pose a serious challenge to healthcare professionals globally during the Coronavirus disease 2019 (COVID-19) pandemic. Nosocomial infection of COVID-19 directly impacts the quality of life of patients, as well as results in extra expenditure to hospitals. It has been shown that COVID-19 is more likely to transmit via close, unprotected contact with infected patients. Additionally, current preventative and containment measures tend to overlook asymptomatic individuals and superspreading events. Since the mode of transmission and real origin of COVID-19 in hospitals has not been fully elucidated yet, minimizing nosocomial infection in hospitals remains a difficult but urgent task for healthcare professionals. Healthcare professionals globally should form an alliance against nosocomial COVID-19 infections. The fight against COVID-19 may provide valuable lessons for the future prevention and control of nosocomial infections. The present review will discuss some of the key strategies to prevent and control hospital-based nosocomial COVID-19 infections.

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1. Introduction

Since the inception of its outbreak, Coronavirus disease 2019 (COVID-19) has spread worldwide, claiming >1,840,000 lives (1). In addition to its global impact, COVID-19 has alarmed the healthcare community on the danger and harm of nosocomial infection. Nosocomial infection of COVID-19 has been discovered and reported in numerous healthcare facilities on a global scale.

A total of 48 COVID-19 cases, including 28 healthcare professionals (HCPs), 13 patients and 7 accompanying persons (ACPs) were associated with a nosocomial infection case in the pediatric dialysis unit of the University Hospital of Münster (Münster, Germany) (2). Among these cases, 4 COVID-19 cases had a 15-min face-to-face contact with healthcare workers without wearing personal protective equipment (PPE) and 7 other healthcare workers were infected while treating patients with COVID-19 at a distance of <2 meters without PPE (2). Carter *et al* (3) reported that 196 nosocomial COVID-19 cases (NC) out of 1,564 patients were from 11 hospitals in the UK and Italy. The mortality rate of NC patients was 27% and the median survival time in NC patients was 14 days (3). Wang *et al* (4) found that 57 cases were infected through hospital-associated transmission among 138 hospitalized patients with COVID-19, including 17 inpatients, 31 HCPs from general wards, 7 HCPs from the emergency department and 2 HCPs from the intensive care unit (ICU). Notably, an index case with abdominal symptoms caused 14 infections, including 10 HCPs with nosocomial COVID-19 infection and 4 hospitalized patients with an atypical abdominal symptom and fever (4). This index case with great capacity to cause infection was presumed to be a superspreader (4). Similar nosocomial infection cases were also found in France (5,6), Canada (7), China (8) and South Korea (9) (Table I). Hence, it is urgent to determine the cause of these nosocomial infection cases.

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2. Transmission model of COVID-19

Nosocomial infections of COVID-19 include exogenous and endogenous infection, and pose a great threat to inpatients, HCPs and ACPs. Exogenous infection, also known as cross infection, is caused by pathogens that directly come from the environment through the HCP's hands or contaminated objects (10). In endogenous infection, patients, especially those who are immunocompromised, are infected by the normal flora from patients or the pathogens from hospital (10). It is hence essential to revisit the modes of transmission of COVID-19.

Source of infection. It is well understood that confirmed patients with COVID-19 are the main sources of infection in human-to-human transmission of COVID-19. Asymptomatic cases and superspreaders may also be potential sources of infection. Additionally, other patients with low immunity and infected patients with no or only mild symptoms may gather in hospital to spread the virus in the community through social interactions. Thus, nosocomial infection acts as a contributing factor of an outbreak (11,12).

Asymptomatic individuals. Asymptomatic patients are those without clinical manifestations but with positive nucleic acid results of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) or chest imaging (13). Asymptomatic individuals may not be ill enough to seek medical care, and this allows them to participate in a larger range of activities. Wang *et al* (14) stated that the transmissibility of asymptomatic patients was fairly limited due to the lack of symptoms, including coughing and sneezing. Hence, they are unlikely to be the major driving force of transmission (14). However, Li *et al* (15) demonstrated that 86% of all patients with COVID-19 infection in China were asymptomatic individuals in the early stage, and they caused 79% of the documented COVID-19 cases with observed symptoms and the rapid spread throughout the country before the travel restrictions. These studies indicate that the discussion on COVID-19 transmissibility of asymptomatic individuals remains to be clarified.

Progress in COVID-19 containment has revealed that the proportion of asymptomatic individuals was higher than previous projections in Wuhan, China (40-50% of all cases) (16). However, some studies have shown that this proportion may be as low as 10% (16,17). It has been reported that asymptomatic individuals can be divided into inapparent cases, which do not appear symptomatic for the incubation period and can even obtain positive results from laboratory tests, and presymptomatic cases (17). During the incubation period, presymptomatic individuals can transmit COVID-19 even before onset of clinical symptoms (18). He *et al* (18) found that the highest infectiousness occurred before symptom onset, and 44% of secondary cases originated from presymptomatic cases. Kimball *et al* (19) reported that a rapid transmission of COVID-19 occurred in a skilled nursing facility in King County (WA, USA). About half of infected individuals were asymptomatic or presymptomatic on the day of nucleic acid testing, and they may therefore contribute to the transmission of COVID-19 (19).

Superspreaders. Individuals who have a greater than average capability of infecting more people are known as superspreaders (20). Medical experts have claimed that superspreaders may trigger a fresh outbreak (19). It is hence necessary to analyze the epidemic chain of transmission of COVID-19 originating from a superspreader considering the increased strain virulence, and the differences in hosts and co-infection with another pathogen should be taken into account (21). Additionally, asymptomatic and mild symptomatic individuals may be another type of infection source of superspreading events (SSEs) due to lack of awareness and containment measures (22). In addition, the combined effects of biology, behavior and environmental factors may lead to superspreading events (20).

During SARS and Middle East Respiratory Syndrome outbreaks, nosocomial transmission was associated with SSEs, and numerous patients, including HCPs and ACPs, were infected with those events (23). Additionally, hospitals are relatively closed environments with often dense populations and poor ventilation, and are therefore more likely to be a transmission site compared with an open environment (24). Moreover, unrecognized or misdiagnosed infection cases in 11 directly transmitted infections, including SARS, were shown to be the main reason of SSEs, followed by the mode of transmission, contact frequency and co-infection (25).

In addition to the aforementioned scenarios, SARS-CoV-2 was detected in some discharged patients, who may still be potential virus carriers (26). Furthermore, it was reported that reverse transcription PCR test results may not fully correlate with transmissibility (27). The World Health Organization (WHO) suggests that patients should be released from isolation >10 days after symptom onset and after >3 additional days without symptoms (28).

Transmission routes. COVID-19 primarily spreads via air droplets and direct contact, but SARS-CoV-2 RNA can also be found in fecal specimens and the virus may be spread via an excretory route (29). Although neonatal infections of COVID-19 have been observed, there is no direct evidence of vertical mother-to-child transmission (30). Fan *et al* (31) analyzed two confirmed expectant mothers, and SARS-CoV-2 was not detected in any of the products of conception and newborns. This analysis indicated that the risk of vertical transmission route of COVID-19 was relatively low (31).

Liu *et al* (32) reported that the trace of SARS-CoV-2 RNA was extremely high in small and non-ventilated mobile toilets in public areas of two hospitals in Wuhan (China), and relatively low in the isolation and ventilated rooms. Notably, some cases of HCP infection in China were associated with aerosol transmission in relatively closed environments, long-term exposures and high-concentration pathogen aerosol environments (33,34). The size of droplets is variable due to the force and pressure at emission, evaporation and environment influence; droplets (5-10 μm in diameter) remain in the air for a short time and settle within 1 m of the source, while aerosols ($\leq 5 \mu\text{m}$) disseminate in the air over long distances (35,36). A large droplet can become an aerosol in less than a second (35). van Doremalen *et al* (37) reported that SARS-CoV-2 is viable and infectious in aerosols for 3 h. It has been shown that the virus can still be detected at a distance of 4 m from patients (38).

Table I. Some nosocomial infection events of COVID-19.

First author, year	Site	Number of infections	Reported timeline (2020)	Events	Patient outcomes	Refs.
Schwierzeck <i>et al</i> , 2020	Münster, Germany	48	N/A	48 cases including 28 HCPs, 13 patients and 7 accompanying persons	N/A	(2)
Carter <i>et al</i> , 2020	11 hospitals in UK and Italy	196	Feb 27-Apr 28	27.0% of patients with nosocomial infection died, and the median survival time was 14 days	53 died	(3)
Wang <i>et al</i> , 2020	Zhongnan Hospital, Wuhan, China	57	Jan 1-28	57 people were confirmed with COVID-19, including 17 inpatients and 40 HCPs	N/A	(4)
Luong-Nguyen <i>et al</i> , 2020	Ile-de-France, France	15	Mar 1-Apr 5	15 patients developed nosocomial COVID-19 infection (all of them had co-morbidities)	2 died, 7 hospitalized and 6 discharged	(5)
Vanhems, 2020	Lyon area, France	8	Mar 10-13	6 cases were infected by 2 potential index cases, including one HCP	2 died	(6)
Elkrief <i>et al</i> , 2020	Canada	47	Mar 3-May 23	The nosocomial infection rate was 19% among 252 patients with cancer and COVID-19	22 died, 7 hospitalized, 3 critically-ill and 15 outpatients	(7)
Lai <i>et al</i> , 2020	Tongji Hospital, Wuhan, China	77	Jan 1-Feb 9	The infection rate of HCPs was 1.1%; 70 HCPs were infected in general clinics or wards, 7 in fever clinics or wards	N/A	(8)
Ji <i>et al</i> , 2020	South Korea	119	Feb 11-Mar 2	The first patient was diagnosed with COVID-19 two days after his death; 119 patients were confirmed with COVID-19	7 died	(9)
Ji <i>et al</i> , 2020	Wuhan Mental Health Center, Wuhan, China	80	Jan 12-Feb 8	~50 patients and 30 HCPs were confirmed with COVID-19	N/A	(9)

N/A, not applicable; COVID-19, Coronavirus disease 2019; HCP, healthcare professional.

If considering only the droplets and direct contact transmission of COVID-19, the recommended distance for HCPs from patients can be decreased to 1 m (35).

Susceptible population. Patients of all ages are susceptible to COVID-19, especially elderly males (>55 years old) with underlying diseases, such as diabetes, hypertension and cardiovascular disease (39). Hospitalized patients in nursing homes or skilled care facilities with moderate to severe asthma, severe heart disease or low immunity (cancer, immunodeficiency or severe obesity) are all high-risk COVID-19 populations of endogenous infection (40).

Another noteworthy aspect of endogenous infection is healthcare-associated infections for critically ill patients caused by other pathogenic microorganisms. For example,

ventilator-associated pneumonia (VAP) is the most common complication of mechanical ventilation (41). The estimated mortality of VAP is 13% (41). Zhou *et al* (42) reported that secondary infections occurred in 27/57 non-survivors of COVID-19, and VAP occurred in 10/32 patients who underwent invasive mechanical ventilation. He *et al* (43) reported that the nosocomial infection rate among patients with COVID-19 was 7.1%; the most common infection was pneumonia, followed by bacteremia and urinary tract infection. The pathogens involved were *Coagulase negative staphylococcus* (27.9%), *Acinetobacter* (20.9%), *Pseudomonas aeruginosa* (14%), *Enterococcus faecium* (11.6%) and *Klebsiella pneumoniae* (9.3%) (43). Under these circumstances, the death rate among patients with nosocomial infection was 15.4% (43).

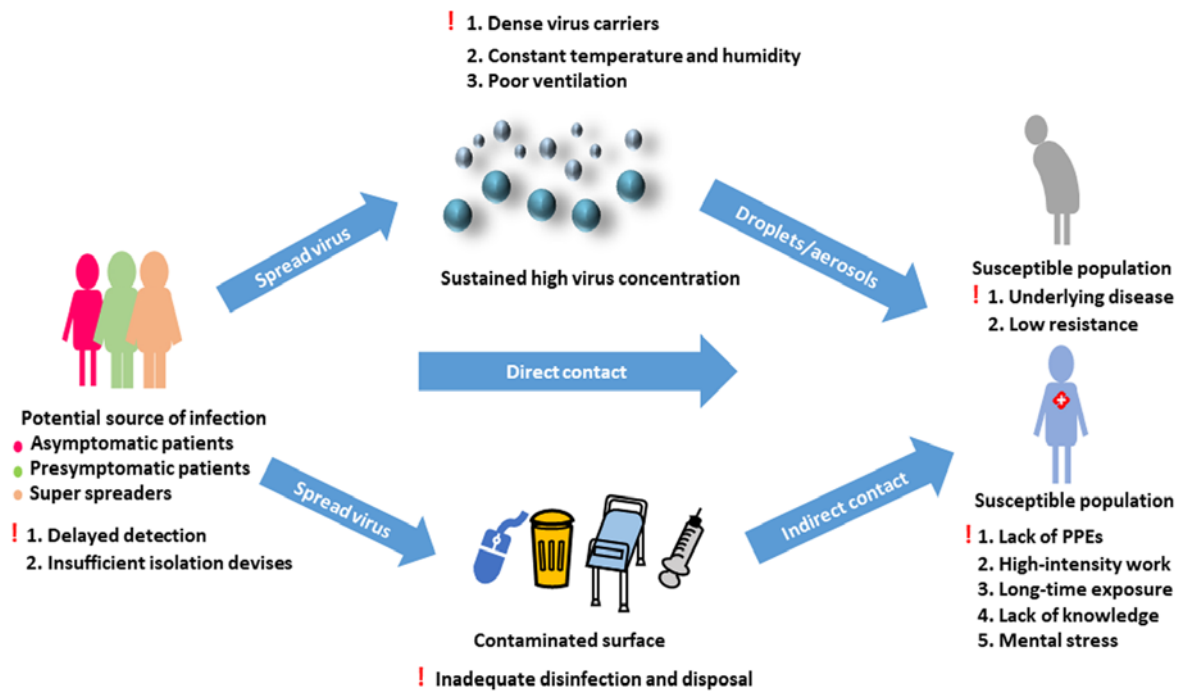


Figure 1. Transmission of Coronavirus disease 2019 in hospitals and factors contributing to the occurrence of nosocomial infection. Exclamation mark indicates the factors facilitating the occurrence of nosocomial infection. PPE, personal protective equipment.

3. Influencing factors associated with nosocomial infection

Lack of self-protection and containment measures may cause a cluster of cases in a hospital. During the early stages of the COVID-19 outbreak, the shortage of PPE and lack of awareness of the importance of personal protections were the main factors of new cases (34,44). In addition, healthcare workers in non-communicable disease departments did not have sufficient knowledge on how to deal with potentially infectious diseases (9). This explains why non-communicable healthcare workers may be more likely to be infected (45). Additionally, in flu season, the transmissibility of the virus was almost always underestimated. Furthermore, numerous patients in long-term nursing facilities with little or no isolation equipment increase the risk of cross-infection (46). Lastly, ACPs may be exposed to the virus without personal protection; therefore, family visits may also increase the potential risk of COVID-19 exposure and infection (9).

The personal protection of HCPs is an important topic. Two studies concluded that HCP-infected COVID-19 cases were mostly due to lack of PPE at the very beginning of the pandemic (33,34). A high-stress work environment may have further weakened the immunity of healthcare workers, and long-time exposure to patients may have rapidly increased their risk of infection (34). Additionally, these healthcare workers may not have received enough professional training in infectious disease control and prevention (33) (Fig. 1).

4. Preventative and containment strategies for nosocomial infection

Monitoring and controlling nosocomial infections are important routines in a hospital, as every hospital should implement effective programs according to its actual condition. This

process typically involves four essential components: i) Conducting scientific surveillance and control measures; ii) Retaining professional epidemiologists; iii) Installing an infection control staff every 250 beds; and iv) A system for statistical analysis of nosocomial infection rates (47).

Triage of patients with COVID-19 for disease management. In the early stages of the COVID-19 outbreak, a large number of hospitals established 3- or 4-tiered patient triage strategies to reduce contact between the susceptible population and potential sources of infection (48,49). At these hospitals, nurses prescreen patients at the entrance of the main lobby by checking the body temperature and scanning health QR codes. The three colors of QR codes (red, yellow and green) correspond to different risk levels (49). Patients would then be divided into different groups according to their body temperatures (Fig. 2).

Patients with a high body temperature would be transferred to a fever clinic through specific routes, accompanied by HCPs with sufficient protection, and epidemiologists would perform detailed COVID-19 checks (48). Other patients with no fever would be allowed for entrance into the general clinic, and specialists of all departments would prescreen for suspected cases according to the patients' body temperatures, epidemiological histories and QR codes (49). Patients with an epidemiological history, including a history of visiting the epidemic area within 14 days, contacting patients with symptoms suggestive of COVID-19 or from an epidemic area within 14 days, and epidemiological linkage with COVID-19, but with normal body temperatures would also receive the same treatments in different areas, while asked to stay in an isolation room for further treatment (48). The suspected patients' condition would be registered in detail and reported to the relevant departments (48).

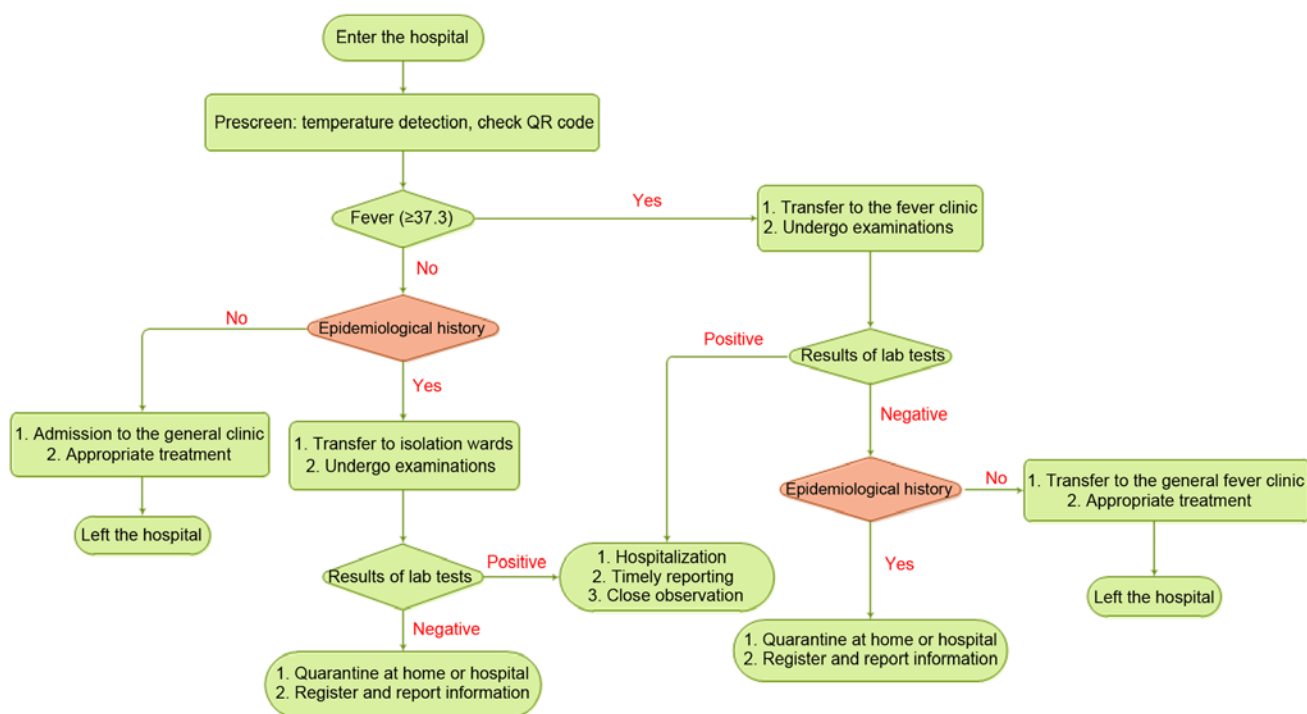


Figure 2. Triage strategies of patients in hospitals.

Reconciling the mismatch between hospital capacity and a large number of patients in a short-term period is a thought-provoking process. Currently, appropriate self-isolation is emphasized for most self-healing and suspected patients to reduce unnecessary visits to the hospital. There are a number of additional tools for reducing the consumption of unnecessary medical resources, such as mobile applications that can track geographic routes so that patients can self-report their own physical conditions and test results of COVID-19. Healthcare institutions can then find out where the outbreak centers are and take corresponding measures and allot materials by analyzing the data collected through these apps (50). Canadian scientists suggested that suspected patients with COVID-19 may be detected and monitored at home while equipped with instruments for measuring body temperature, blood pressure and heart rate (51). Additionally, HCPs can communicate safely with patients through remote monitoring systems (51). The effectiveness of home care depends on factors including professional guidance and management, and adequate measurements for nursing at home in cases of suitable conditions of the patients (52).

Furthermore, patients can be screened by telephone before they enter the hospital in order for HCPs to prepare for isolation before patients who need urgent care arrive to the hospital (53). In addition, internet hospitals in China provide medical consultation services for the public in order to alleviate the public's alarm, impart personal protection knowledge and correct inappropriate medical behaviors, thereby reducing unnecessary visits to hospitals (54).

Frontline HCPs have a distinctly higher risk of infection, especially those who re-use PPE or do not have adequate PPE (55). Htun *et al* (56) proposed a Staff Health Surveillance System to monitor employee travel experience, sick leave and detailed information, and record body temperature and N95

mask usage. These data provide important references for the management and protection for HCPs.

Specially redesigned wards in hospitals for patients with COVID-19. The Chinese Health Commission specifies that fever clinics are to be divided into special consulting rooms, specifically used for receiving patients with a high risk of COVID-19, and general consulting rooms, to receive patients with a low risk or a clear non-COVID cause of fever (48). These fever clinics, also known as wards, are located in a separate area and the entrance for patients is different from that of healthcare workers (49). The wards provide a convenient way of isolation from the outside and they are divided into two parts: One for isolating confirmed cases, which can host multiple patients, and the other for suspicious patients, where only one person is allowed per room (57). A buffer zone is located between the clean, semi-clean and contaminated areas to reduce staff exposure to infected cases, and HCPs take strict self-protection measures and go through disinfection before entering and leaving the contaminated area (58). Ventilation of the isolation ward is required to reach 60 l/s, and the distances between beds are set to at least 1 m (59). The number of isolation rooms is determined based on the epidemic condition and the number of patients received.

It is important to design and install appropriate isolation procedures, such as physical barriers or partitions to guide patients to different areas, curtains in the shared area to isolate patients, and installing and maintaining air treatment systems with directional, filtering equal capacity to maintain air circulation (60). Tang *et al* (61) suggested that the doors and windows of the isolation room should be kept closed to avoid reverse airflow.

High-risk treatment procedures that should be avoided. According to the transmission modes of COVID-19,

treatment procedures that produce droplets and aerosols are high risk. Loeb *et al* (62) demonstrated that auxiliary intubation, suctioning before intubation and operating an oxygen mask were high-risk activities. Patients' secretions, saliva or blood may aerosolize to the environment while receiving treatment, especially in the stomatology department, with possible apparatus contamination (63). Hence, the risk of cross-infection increases through direct contact (63). Moreover, the virus can be detected in conjunctival swabs of patients with eye symptoms (64), indicating that patients who received slit lamp examination and direct ophthalmoscopy, as well as ophthalmologists, have a high risk of infection (65).

Incidentally, each medical department should suspend all unnecessary inspections to decrease the chance of transmission (65); only urgent surgeries should be arranged at the end of the day to reduce the risk of hospital infection (63,66). Additionally, the number of health care assistants should be minimized, and patients who are at different risk levels of infection should be placed separately to reduce cross-infection (67).

The risk of nosocomial infection can be analyzed from two aspects: i) Daily risk of exposure, and ii) Total number of days of exposure. It has been shown that patients in the high daily risk department for a short time may have the same chance to be infected as patients in the low daily risk department for a long time (68). For each department, it is necessary to decrease the daily risk through various protective and disinfection measures, and shorten the treatment time of patients by reducing unnecessary treatment procedures (69).

Environmental surveillance and disinfection in wards and HCP offices should be enhanced. van Doremalen *et al* (37) has reported that the half-life of SARS-CoV-2 in aerosol is 1.1-1.2 h and has a longer viability period on stainless steel and plastic surfaces, with half-lives of 5.6 and 6.8 h, respectively. Constant humidity and temperature for an extended period of time in the hospital may further prolong the survival period of the virus (32). Coronavirus is sensitive to ultraviolet light and heat, and most disinfectants (except for chlorhexidine) can effectively inactivate the virus (70,71). Kampf *et al* (70) reported that using 62-71% ethanol, 0.5% hydrogen peroxide or 0.1% sodium hypochlorite can effectively inactivate human coronavirus within 1 min; however, 0.05-0.2% benzalkonium chloride or 0.02% chlorhexidine and gluconate are less effective.

The virus can be widely distributed on the floor, computer mouse, trash cans and even bed handrails, and can be detected in 4 m of air surrounding a patient (38). Compared with contaminated areas, clean and semi-clean areas exhibited more sites where the virus was detected. Moreover, the contamination in isolation wards was even worse than that in ICUs (58,72). These results indicate that HCPs may be exposed to a higher risk in isolation wards and semi-clean areas instead of contaminated areas. Therefore, it is important to enhance daily disinfection, particularly on key surfaces such as handle rails, switches and computer keyboards.

The wards of discharged patients should be fully disinfected. Sheets, curtains, ventilation, lighting and all surfaces should be carefully cleaned (73). For medical procedures that may generate aerosols, effective air isolation measures, including single rooms, negative pressure, frequent ventilation and powered air-purifying respirators, are required (74). Each

department should formulate their own disinfection strategies, ensuring that all surfaces are cleaned and disinfected after daily operations (63,65,75).

Self-protection is important for HCPs

PPE. Masks, goggles, protective clothing and good hand hygiene directly decreases the risk of nosocomial infection (76). Casanova *et al* (77) found that the coronavirus can survive >24 h on an N95 respirator, and at least for 4 h on other PPE. Therefore, it is important to train HCPs on how to wear and remove PPE correctly, and promptly dispose of used PPE. The correct order of wearing PPE is as follows: Hairnet, gown (with a back closure, may require two people), filter mask, goggles and finally two layers of gloves, with the inner layer covering up the wrist (75).

In order to improve the efficiency of protective devices, the usage of PPE is determined by the risk level of each patient, and the prevention measures are formulated according to the risk assessment of the epidemic (66). The WHO recommends using PPE for HCPs depending on the aerosol-generating procedures in different settings and the infection risk of patients. HCPs should wear medical masks and eye protection when screening patients without direct contact within 1 m (78). HCPs should use respirator N95 of FFP2 or FFP3 standard, gown, gloves, eye protection (goggles or face shield) and apron when collecting diagnostic respiratory samples in enclosed spaces or directly taking care of patients with COVID-19 (where aerosol-generating procedures are frequently performed) (78). When aerosol-generating procedures are not performed, the respirator can be replaced by a medical mask, and the apron is not required. When HCPs treat patients with symptoms suggestive of COVID-19, HCPs should use a medical mask, gown, gloves and eye protection (78). In addition, lab technicians who may handle the specimens from suspected or confirmed patients should use a medical mask, eye protection, gown and gloves, and should maintain a physical distance of at least 1 m (78).

Hand hygiene. Transmission through HCP hands in contact with contaminated surfaces also increases the risk of exogenous nosocomial infections (79). Hand cleaning and disinfection are the main steps that can stop pathogens from being transmitted from the patient to the HCP (80). HCPs in all departments need to thoroughly wash their hands before examination, after touching patients, after collecting patients' oral mucosa, blood and body fluids, and after touching equipment without sterilization (81). Pessoa-Silva *et al* (82) investigated the hand hygiene conditions of 149 newborn nursing staff, and the results revealed that the use of gloves did not completely protect HCP hands from bacterial contamination. Since numerous HCPs still believe that the purpose of using gloves is only for self-protection rather than protecting patients, hand washing compliance needs to be further reinforced. Hands should also be strictly sterilized before wearing gloves to avoid infection caused by broken gloves (83).

Education and training for HCPs and the public can decrease the risk of transmission. Patients in community or hospital isolation should strictly comply with medical guidance and wash their hands with water or soap for at least 20 sec or with

an alcohol-based hand sanitizer, avoid touching their eyes, cover their nose and mouth with tissues when coughing or sneezing, and disinfect objects and surfaces that are always touched (84). Patient education will increase awareness for hand hygiene (85). Based on a survey performed on a Chinese population, 98% of the participants would wear masks when they went outdoors; additionally, participants with a high socioeconomic status, especially females, were more educated about COVID-19 and complied better to PPE usage and hand hygiene guidance (86).

Sufficient knowledge and on-premises work experience may improve the ability of HCPs to better handle COVID-19, since incorrect attitudes and practices directly increase the risk of infection (87). In the early stages of the outbreak, the health administrative department of hospitals in China conducted professional training for medical workers through demonstrations, videos and other methods, including personal protection measures, medical waste disposal and emergency treatment agreements, and experts supervised the entire process of professional training. Before participating in the treatment of COVID-19, HCPs were subjected to medical examination and daily self-monitoring of respiratory symptoms (88). High-risk HCPs who were pregnant, >55 years of age or had a history of chronic diseases or acute fever were exempted from SARS-CoV-2-associated work (89).

Disposing medical wastes correctly to reduce avoidable transmission. During the COVID-19 outbreak, the demand of PPE and medical supplies increased dramatically. Wang *et al* (90) estimated that the daily demand for masks reached 900 million in China. There were too many medical wastes to be disposed of properly to reduce the potential risk of transmission among HCPs, patients and the public. Different types of waste should be collected in specific containers with labels to avoid accidental injury of cleaning staff and decrease the financial costs on waste disposal (91). Installing temporary disposal facilities and incinerators may relieve the pressure of a sharp increase in waste, and the risk of transportation may be influenced by the haul distance and location of facilities, which should be taken seriously according to economic costs and distance (92). Medical waste disposal procedures include collection and separation of medical wastes, transportation facility, proper waste disposal and staff protection and training (93). The WHO has given detailed advice on waste collection and destruction, as well as personnel training and protection (94). According to this advice, Chinese scientists gave guidance on the disinfection of wastes during the COVID-19 outbreak (95).

Logistic support measures are sustaining epidemic prevention efforts. With the surge in the number of infected cases, the demand of transportation vehicles and HCPs for transportation of patients and equipment for critically ill patients also increased sharply. Deployment and supply of personnel, equipment and drugs are of significance in treatment efficiency and containment of any epidemic. A fast and economical logistics model should be established according to the outbreak situation in various places. He and Liu (96) proposed that the sensitive-exposure-infection-recovery model may be considered as a basis of predicting the medical needs of various regions

and formulating a material distribution plan. The 'Eagle-Eyed Observer' is a logistics support system that can monitor the physiological index of HCPs before and after entering the isolation ward, guide the HCPs to use PPE correctly and deal with used PPE, monitor the patient's situation and ward environment, and even organize medical supplies properly (97).

5. Conclusion and future perspectives

COVID-19 can be transmitted by direct contact with blood, body fluids, tissues of patients, droplets and surfaces contaminated by the virus. To date, nosocomial infections have occurred to varying degrees in different countries around the world. In hospitals, high population density, large numbers of susceptible people and the gathering of potential sources of infection are all contributing factors for nosocomial infections. A great amount of effort goes into nosocomial infection control of COVID-19. It is necessary to call for doctors' First Visit Responsibility in saving patients with COVID-19 and determine the handling of HCPs with direct or continuous exposure to infected patients.

Technology has played a crucial role in the prevention and control of COVID-19 in four ways. Firstly, artificial intelligence (AI)-driven robots or AI-assisted equipment have been very effective in fighting against the virus. It takes 1 min for a robot equipped with an AI-enabled fever-screening system to check the temperature of 200 people in an efficient and accurate manner; robot deliveries supported by cutting-edge technologies show promising potential for reducing direct exposure to the highly contagious virus (98). Secondly, digital technologies, such as big data and cloud computing, have been heavily utilized in containing and preventing outbreaks. There is an application prospect for the use of digital technologies in the evaluation of disease outbreaks. Thirdly, remote healthcare services backed by 5G communication technology are among the potential applications to ensure communication services for hospitals in different regions. Finally, remote visual medical treatment systems may aid in assisting front-line practices for healthcare workers to work remotely without direct exposure or continuous exposure to infected patients. This comprehensive network may serve an important role in minimizing the incidence of nosocomial infection.

Nosocomial infection constitutes an important part of an epidemic, especially in high-risk populations with insufficient prevention and control measures, including psychiatric hospitals and long-term care facilities. Improving the ability of detecting the mild or asymptomatic and presymptomatic individuals as early as possible is the key point in the current stage of the epidemic. Maintaining a safe distance, isolation measures, adequate material supplies and advanced telemedicine are important measures to control the epidemic. Limitations in the present review of the small-scale cases with COVID-19 infection are due to the finite number of nosocomial infection cases that have been reported. Further research on the association between nosocomial infection with subtypes of COVID-19 infection, such as the ordinary, severe or critical type, the days in hospital, ICU or relapse, and mutual infections during hospitalization, are deemed valuable for guiding clinical nursing and treatment. The present review indicates that once an epidemic occurs, a comprehensive

analysis network may provide a powerful guideline for the next unknown virus or even the resurgence of COVID-19, and may pave the way to handle similar public health emergencies in the future.

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Availability of data and materials

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Authors' contributions

QD and DZ contributed to the writing, reviewing and editing of the manuscript. QD and WH confirmed the authenticity of the data. QD, XL, QX, TW and HJ provided resources and created the figures. DZ and WH were involved in the conception of the study and provided supervision. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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