



Review Article

Personal protective equipment during the coronavirus disease (COVID) 2019 pandemic – a narrative review

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Summary

Personal protective equipment has become an important and emotive subject during the current coronavirus disease 2019 epidemic. Coronavirus disease 2019 is predominantly caused by contact or droplet transmission attributed to relatively large respiratory particles which are subject to gravitational forces and travel only approximately 1 metre from the patient. Airborne transmission may occur if patient respiratory activity or medical procedures generate respiratory aerosols. These aerosols contain particles that may travel much longer distances and remain airborne longer, but their infective potential is uncertain. Contact, droplet and airborne transmission are each relevant during airway manoeuvres in infected patients, particularly during tracheal intubation. Personal protective equipment is an important component, but only one part, of a system protecting staff and other patients from coronavirus disease 2019 cross-infection. Appropriate use significantly reduces risk of viral transmission. Personal protective equipment should logically be matched to the potential mode of viral transmission occurring during patient care – contact, droplet or airborne. Recommendations from international organisations are broadly consistent, but equipment use is not. Only airborne precautions include a fitted high-filtration mask, and this should be reserved for aerosol generating procedures. Uncertainty remains around certain details of personal protective equipment including use of hoods, mask type and the potential for re-use of equipment.

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Introduction

Personal protective equipment (PPE) is a current hot topic – probably the most talked about and emotive subject for front-line healthcare staff working with patients with coronavirus disease (COVID-19). There are two main related problems: shortages of equipment; and inappropriate use of equipment. This review seeks to add some clarity regarding modes of transmission of COVID-19, what PPE is recommended, when and why (Box 1). It also explores where uncertainty exists. It uses a simple nomenclature for PPE based on mode of transmission. Its focus is predominantly UK-centric and readers from elsewhere should consult local guidance.

Mode of viral transmission

The highest viral load of severe acute respiratory syndrome corona virus 2 (SARS-CoV-2), the virus causing COVID-19, is in sputum and upper airway secretions [1]. Whereas viraemia can occur, blood-borne infection is not considered a major source of transmission [1]. The virus is predominantly spread by droplet and contact routes [2]. Droplet transmission is via larger respiratory particles, generally above 5 µm diameter, which are subject to gravitational forces. These tend to travel no more than 1 m. A 2-m limit on contact is therefore precautionary. Contact transmission occurs because once the virus is on a surface, it will remain there and will be a potential source of infection

Box 1 Key points regarding personal protective equipment (PPE)

- 1** Coronavirus disease is predominantly transmitted by contact or droplet transmission.
- 2** Coronavirus disease can become aerosolised by 'aerosol generating procedures' and then airborne transmission is possible.
- 3** Personal protective equipment is only one part of a system to protect staff and other patients from COVID-19 transmission
- 4** Personal protective equipment recommendations from international organisations are broadly consistent; PPE use is not.
- 5** Appropriate use of PPE significantly reduces the risk of viral transmission and infection.
- 6** Personal protective equipment should be matched to the potential mode of viral transmission – contact, droplet or airborne
- 7** Only airborne PPE includes an FFP3 mask and this is reserved for aerosol generating procedures.
- 8** Overuse of PPE is a form of misuse.
- 9** Misuse of PPE depletes limited stocks, leads to avoidable shortages and increases risk to staff.

for a period of hours or even days [3]. This creates the risk that healthcare workers touching that surface will become contaminated and subsequently they, or others, will become infected. Airborne transmission occurs when smaller respiratory particles (generally $< 5 \mu\text{m}$) circulate in the air for prolonged periods.

Viral particles are absorbed via the respiratory mucosa and potentially across the conjunctivae. Particles smaller than $10 \mu\text{m}$ are most likely to penetrate deeply into the lung and cause infection [4]. The coronavirus is not currently considered to be an airborne virus so airborne precautions are not routinely necessary [2]. However, certain procedures – particularly those associated with airway management – can create aerosols containing virus that linger in the air and therefore risk transmission over distances beyond 2 m. Aerosol generation occurs when air accelerates across a fluid surface, but whether that aerosol has infective potential is impacted by many factors, including where the fluid originates (e.g. upper airway, vocal cords or lower respiratory tract) and these may differ according to the procedure. When a respiratory aerosol generating procedure is undertaken (Table 1), and until the room is

Table 1 Aerosol generating procedures, modified from [2]. The numbers in brackets indicate the rank order of decreasing risk for the top four procedures as reported by Tran et al. [4].

Respiratory aerosols

- Tracheal intubation, extubation and related procedures (1)
- Non-invasive ventilation (2)
- Tracheostomy and front of neck airway (3)
- Face-mask ventilation (4)
- All forms of positive pressure ventilation of the airway (irrespective of mode) if the airway is not sealed
- Open tracheal suctioning
- Bronchoscopy and broncho-alveolar lavage
- Induction of sputum
- High-flow nasal oxygen
- Certain dental drilling procedures
- Nasogastric tube insertion^a
- Chest compressions and/or cardiopulmonary resuscitation^a

Blood or tissue fluid aerosols

- Surgery procedures in which high-speed devices are used (e.g. pulse lavage, drilling, sternotomy)

^aChest compressions and/or cardiopulmonary resuscitation and nasogastric tube insertion are described by some as aerosol generating procedures but are currently under review.

clear of aerosol (the viral clearance period), the level of PPE worn should be at the level of airborne protection.

Aerosol generating procedures can usefully be separated into respiratory and surgical: only respiratory aerosol generating procedures aerosolise respiratory or upper airway secretions. These are likely to have a higher viral content and pose a greater risk of transmission than surgical aerosol generating procedures which aerosolise blood and tissue fluid.

Respiratory particles may be spread while breathing, speaking, coughing or sneezing. The size of the particles, their site of origin in the respiratory tree, their infective load and infective capacity will vary during these activities [4]. For instance, coughing may be preceded by a deep breath leading to fluid generation from opening up previously collapsed bronchioles [4]. Coughing and sneezing expel a cloud of respiratory particles of many different sizes, ranging between < 1 to $> 500 \mu\text{m}$ [4] or even up to $2000 \mu\text{m}$ [5]. A sneeze contains more particles than a cough and for both the degree of dispersal is dramatically reduced by the patient wearing a fluid-resistant surgical facemask [2]. Traditionally, coughing and sneezing are not included in the list of aerosol generating procedures. One estimate is that 99.9% of the fluid volume is in larger droplets subject to gravitational impact and travelling only a short distance [5]. For this reason, the risk of transmission of infection from

sneezing or coughing is judged to be from droplet and contact transmission rather than airborne transmission [5]. However, the dichotomy into $> 5 \mu\text{m}$ and $< 5 \mu\text{m}$ particles leading to droplet or airborne spread, respectively, is likely to be simplistic, with aerosols being maintained over a wider range of particle sizes [4]. In a research setting, detection of the smaller airborne particles is technically highly challenging. Early studies may have biased against detection of small particle aerosols and therefore favoured droplet spread as a mechanism of spread [4]. Whether smaller particles in aerosols retain infective viral material is also uncertain [4]. Several publications have highlighted the complex nature of cough 'cloud dynamics' and questioned whether corona viruses [6] including COVID-19 may also be spread by airborne transmission [3, 6, 7, Santarpia et al., unpublished observations]. Of note, an experimental study that reported virus persisting in the air for 3 h was undertaken in conditions that do not mirror those found clinically, making it difficult to interpret [3]. In a scientific statement on 29 March 2020, the WHO recommended droplet and contact precautions routinely and airborne precautions for aerosol generating procedures [8]. This is consistent with most countries' guidance [2, 9–13].

Aerosol generating procedures increase the risk of healthcare worker infection and should only be undertaken when necessary. Where possible, aerosol generating procedures should be undertaken in a single well-ventilated negative-pressure room with the doors shut. Only those staff who are needed to be present should be. In many settings this ideal is unachievable. Rapid air turnover in the room is more important than whether it is at negative or positive pressure. Rooms with a low rate of air exchange or with ventilation turned off should be avoided.

Types of aerosol generating procedures

Not all respiratory aerosol generating procedures will be of the same risk. It is notable that intubation is consistently rated as high risk and that both this and mask ventilation are considered to be at the higher end of the scale of risk [14]. Anaesthetic techniques that reduce coughing, positive pressure ventilation via an unsealed airway and contact exposure to respiratory secretions will reduce risk, but airborne precaution PPE is recommended for all staff in the room during airway management [2, 15].

High-flow nasal oxygen is worth considering in more detail. The extent to which high-flow nasal oxygen is aerosol generating is debated and uncertain [16]. New machines likely cause less dispersal than older machines. The extent of bacterial spread in patients during high-flow nasal

oxygen use in patients with bacterial pneumonia is low [17], but viral spread has not been studied. A systematic review judged risk of infection transmission to be low [14] but this was based on only one study [18]. High-flow nasal oxygen in patients with COVID-19 may prevent or delay tracheal intubation but there is a lack of consensus as to whether it reliably reduces mortality in acute respiratory failure [19–23]. It has been widely used in China and Italy during this epidemic. Some older devices consume large amounts of oxygen, but more modern devices use entrained room air and only small amounts of oxygen supply, which is beneficial if shortage is anticipated. When high-flow nasal oxygen is used, airborne precaution PPE is currently recommended [2]. Low-flow nasal oxygen (i.e. $< 5 \text{ l}\cdot\text{min}^{-1}$ via normal nasal cannula) is likely to be of even lower-risk and is not considered an aerosol generating procedure.

Supraglottic airway (SGA) placement or use is not listed as an aerosol generating procedure by most sources, but it is logical that placement of an SGA is aerosol generating. If an airway leak persists after SGA insertion and controlled ventilation is used, the risk may persist. Careful patient selection; restriction only to appropriate operations; use of an SGA design likely to have a good seal; meticulous insertion technique; use of controlled ventilation with low airway pressures; or the use of spontaneous ventilation, may all reduce the extent of airway leak and potential for aerosol generation. Use of a second generation SGA is likely to improve airway seal. The drain port of a second-generation SGA may risk potential secretion dispersal if the airway seal is poor, but there is currently no evidence to support or refute this.

Types of PPE masks

A fluid-resistant (Type-IIIR) surgical facemasks is used to protect against droplets. If worn by the patient, it will minimise dispersal of large respiratory droplets which will protect staff against both droplet and contact transmission [24]. If worn by staff, it will protect against droplet transmission, when within 1–2 m of the patient. Risk reduction by at least 80% is estimated [2].

The terms filtering facepiece FFP2, FFP3 and N95 are used in reference to high performance filtering masks. Filtration is achieved by a combination of a web of polypropylene microfibres and electrostatic charge. There are three classes of protection, adhering to the European standard EN 149 + A1:2009 [25], each with an assigned protection factor which indicates the degree to which the mask will reduce concentration of the hazardous substance. For FFP1, FFP2 and FFP3 these are 4-, 10- and 20-fold, respectively [26]. In the detail of the standard it states that

Table 2 Modes of viral transmission, settings where they are relevant and matched types of personal protective equipment.

Mode of transmission	When to use in a patient being treated as COVID-19 +ve	What is it?
Contact precautions	> 2 m away from patient	Gloves Apron
Droplet precautions	Within 2 m of patient	Gloves Apron Fluid-resistant surgical mask ± Eye protection ^a (risk assess)
Airborne precautions ^b	Aerosol generating procedure	Gloves Fluid-repellent long sleeved gown Eye protection ^a FFP3 mask

The levels of protection are incremental: droplet precautions are also designed to prevent contact transmission; airborne precautions also to prevent droplet and contact transmission. Some recommend a fluid-resistant surgical face mask in all clinical areas.

^aEye protection may be goggles or a visor. Personal spectacles are insufficient.

^bIn ‘hot spots’ where aerosol generating procedure are regularly undertaken airborne precautions may be worn on a sessional basis: the normal attire is supplemented by a plastic gown and this and the gloves are changed between patients [2].

the total inward leak of particles must not exceed in 92% of exercise tests: 25% for FFP1; 11% for FFP2; and 5% for FFP3. It also states that the mean inward leak in 8 of 10 wearers should not exceed: 22% for FFP1; 8% for FFP2; and 2% for FFP3 masks. Finally, the penetration of test aerosols, both saline and paraffin oils, should not exceed: 20% for FFP1; 6% for FFP2; and 1% for FFP3 masks. These tests are to be performed on masks as delivered and during simulated use. Perhaps this last provides the best measure of filtration, meaning that the overall filter efficiency of FFP1, FFP2 and FFP3 masks is 80%, 94% and 99% [25].

The N95 designation means that under test conditions (certified under 42 CFR 84 of National Institute for Occupational Safety and Health and the United States CDC), the respirator blocks at least 95% of solid and liquid aerosol test particles. The N, R and P masks describe their increasing resistance to oils and the number (95, 99 or 100) refers to the minimal percentage of particles filtered under test conditions [27]. Filtration performance during use is likely to be higher than indicated, as testing is undertaken in the ‘worse case setting’ of high air flow and using high penetrating aerosols (0.3 µm diameter).

As such, the FFP3 is likely to be twice as effective as the FFP2 mask, and broadly both are equivalent or superior to an N95 mask. These masks should be fluid resistant when used for medical purposes. FFP2/3 and N95 masks do not work unless they fit well to the face and create a seal. Individual mask fit-testing should be undertaken by all relevant members of staff before they are worn on clinical duty. All the above tests assume the face seal exists. This requires a large stock of equipment simply in order to test the equipment. Done properly,

mask fit-testing should have a failure rate < 5% and if it is much higher this should bring into question whether the correct testing procedure is being undertaken. FFP2/3 and N95 masks should be fit-checked before each use, that is, the user should confirm a seal before entering the area of risk. The WHO recommends that FFP2/3 and N95 masks can be, if undamaged, for up to 4 h, which is approximately the median healthcare worker tolerance time, though this is highly variable [28, 29].

Appropriate levels of PPE

Standard infection control procedures should already be in place. Those described here are specific to reducing the risk of viral transmission to the healthcare worker. The PPE used in each setting should be appropriate to the mode of infection. Currently multiple terms are used to describe PPE, which seem undefined, inconsistently used and do not match PPE to the modes of infection transmission.

The types of transmission and the protection required to combat that mode of transmission are summarised in Table 2. Use of this nomenclature should improve clarity of purpose and actions when using PPE.

Contact precaution PPE is appropriate for staff in the same room as patients with COVID-19, and where aerosol generating procedures are not undertaken, but who remain more than two metres from the patient (some sources state 1 metre but that allows no margin for error). Droplet precaution PPE is appropriate when caring for a patient or being within two metres. Eyewear is added based on a risk assessment. The patient should also wear a fluid-resistant surgical facemask. Airborne precaution PPE is recommended only when aerosol generating procedures are being

undertaken and after this until air exchanges have reduced virus sufficiently. It should be worn by all those in the room during this period.

The levels of protection are incremental: droplet precautions are also designed to prevent contact transmission; airborne precautions also to prevent droplet and contact transmission. This could be made clear by labelling the classes of precautions in full, or using the letter C, D + C, A + D + C but these solutions seem cumbersome and unclear, respectively, so it is perhaps best simply to refer to them by the highest level of protection that they aim to protect against, with all lower levels implied.

Public Health England recommends airborne precautions are used in 'hot spots' where aerosol generating procedures are regularly performed, if any suspected COVID-19 patients are present – these include intensive care unit, operating theatres where aerosol generating procedures are done, and emergency department resuscitation bays [2]. In these settings airborne precautions may be kept on for a whole 'session': the normal attire is supplemented by a plastic gown and this and the gloves are changed between patients [2].

Viral clearance periods

In hospitals, room ventilation will clear viral aerosols fairly quickly. Each 'air exchange' removes approximately 63% of the virus [30, 31]; after n room exchanges, the remaining viral load is 0.37^n . After two exchanges, there is 14% and after five air exchanges $< 1\%$ (0.37^5) of the original viral load in the room, respectively. If there are 12 air exchanges per hour, five exchanges will take 25 min. This may be the case in ICU. If there are 25 air exchanges per hour, five air exchanges will take 12 mins. This may be in a well-ventilated operating theatre. In general wards, approximately six air changes typically occur per hour. Whereas Public Health England guidance states that 'two air changes is pragmatic' [2], it does not state whether there is evidence this is sufficient to reduce risk.

While negative-pressure rooms are recommended for aerosol generating procedures, it is likely that in many settings during an epidemic this will not be practical. In some locations, engineering modification can change a positive pressure room or entire ward to a negative pressure. Having a room with good ventilation, that is, a high rate of air exchanges, is likely to be more important than whether it is at positive or negative pressure.

Preventing cross-infection

There is considerable focus amongst staff on the equipment component of PPE and of infection control. It is vital to

remember, and easy to forget, that PPE is only one part of a system to prevent contamination of those working near patients with COVID-19 which might then pose a risk to those staff, other staff and patients.

Other elements of a system to reduce cross-infection include

- 1 Avoidance of patients, visitors or staff who have or have been exposed to COVID-19 entering hospitals without reason.
- 2 Scrupulous hand-washing and personal hygiene.
- 3 Managing patients with known or suspected COVID-19 entirely separately from those without it, through isolation or cohorting.
- 4 Restricting personnel (both staff and visitors) in the location of patients with COVID-19 to only those who are needed.
- 5 Cleaning regimens with a least twice daily decontamination of surfaces and equipment.
- 6 Minimising unnecessary patient and surface contact during patient care.
- 7 Best practice in donning, doffing and disposal of PPE.
- 8 Appropriate disposal of all single-use equipment after use and decontamination of reusable equipment strictly in line with the manufacturer's instructions.
- 9 Appropriate waste management.

A number of organisations have produced guidance on PPE which is broadly consistent, including: the World Health Organization [32]; the European Centre for Disease Control [13]; Public Health England [2]; and the European Society of Intensive Care Medicine and Society of Critical Care Medicine [33]. Each organisation states that airborne precautions consist of: fit-tested and fit-checked high filtration mask; goggles or visor; long sleeved fluid-repellent gown; and gloves. Increasingly, all guidance includes the use of FFP2 masks [13, 23, 32] although some currently only refer to FFP3 masks [2].

Personal protective equipment should be simple to remove after use without contaminating the user. Experience from the SARS epidemic in Canada, which was associated with high rates of healthcare worker infection, indicates that complex PPE is likely to increase the risk of contamination during removal. It should be disposable whenever possible and disposed of appropriately, immediately after removal. A 'buddy system' with an observer using a checklist is recommended to ensure putting on (donning) and removal (doffing) of PPE is performed correctly. Training and practising PPE use before patient management is essential for staff and patient safety.

PPE overuse and misuse

There are considerable stocks of PPE in the UK. The government has recently committed to improve supply to those who need to use it and enrolled the army to maintain the supply chain. However, such is the global demand that stocks are limited and while supply chains (many of which are reliant on China) are fragile, supplies will remain uncertain. For all the reasons described above, it is important to ensure PPE is used appropriately and not wastefully. Using a different or higher level of PPE than is required is a form of misuse and may mean that supplies are inadequate in the future. Rumour, PPE misuse and confusion can contribute to healthcare worker infection [34].

Transmission-based precautions, that is, precautions additional to standard infection control precautions, were not initially recommended when treating patients without risk factors or symptoms of COVID-19. However, as rates of infection in the community increase significantly, this becomes a pragmatic solution and is likely imminent in the UK. The UK government has published specific guidance on when to use an FFP3 mask [33] and a specific information document on the topic [35]. The WHO has recently published a document relating to conservation of PPE stocks globally that focuses on appropriate PPE use, avoiding PPE overuse and maintaining supply chains [28].

Unanswered questions

A Cochrane review of evidence relating to PPE and protection of healthcare staff exposed to contaminated body fluids illustrates the lack of robust evidence in this area – all interventions studied were supported by no more than one paper and all evidence summaries were rated as very low evidence [36]. This review reports that gowns provide better protection than aprons; that doffing supported by verbal instructions reduces errors; and a single simulation study suggests that use of a pressurised air-purifying respirator may reduce contamination compared with more conventional PPE [37]. Overall, there is a lack of high-quality evidence and the evidence available is from generally small studies in simulation settings with an almost complete absence of clinical studies examining relevant clinical outcomes.

The evidence base for use of one sort of mask (e.g. FFP3/FFP2/N95) over another (e.g. surgical facemask) is not as robust as might be expected, with a lack of clear evidence of benefit from high filtration masks [38]. It is likely that breaches in testing, fitting and personal breaches of use contribute to this. Classification of procedures as aerosol generating is also imperfect and the degree to which each

puts staff at risk of disease transmission is not rooted in clear science. Emerging literature from China shows very low (or zero) rates of healthcare worker infections associated with tracheal intubation when PPE was appropriately used [24, 39, 40].

Evaluation of the possibility of decontaminating and reusing N95 masks has been undertaken, with early results suggesting promise for both steam and UV sterilisation. However, these results are not yet peer reviewed or published and cannot be widely applied. Repeated steam application led to degradation of filtering capacity and alcohol and chlorine-based solutions damaged the fabric. For the time being single-use masks should remain just that [41].

None of the published guidance describes use of protective head gear or hoods, though this is widely used in some countries. There is some evidence that double gloving for tracheal intubation might provide extra protection and minimise spread by fomite contamination of equipment and surroundings [34]. Locations reporting low rates of healthcare worker infection after involvement in tracheal intubation may have used PPE that exceeds the airborne precautions described above. In some reports, after intubation procedures and carefully doffing of PPE, staff showered and oral, nasal and external auditory canal disinfectants were recommended [42]. In some locations, staff involved in intubation were also isolated from families and kept under surveillance for infection for 2 weeks before return to work [40]. Whether such extreme precautions are useful, practical or necessary to maintain low rates of healthcare worker infection is entirely unknown.

Summary

Overall, there is evidence that the use of PPE does reduce rates of disease transmission and protects staff. It is essential that staff understand the purpose of PPE and its role as part of a system to reduce disease transmission from patients to staff and other patients. It is equally important that staff use it appropriately to preserve what may be limited stocks to ensure there is sufficient supply for necessary use throughout the epidemic surge.

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