REVIEW ARTICLE

Basic Principles of Disinfection and Sterilization in Intensive Care and Anesthesia and Their Applications during COVID-19 Pandemic

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Abstract

Understanding the concepts of disinfection, sterilization, cleaning and asepsis is of prime importance to prevent transmission of infection to patients and to protect healthcare workers (HCWs). Proper disinfection of surfaces after cleaning, an important consideration at all times, has assumed special significance during the current pandemic. The global shortage of disposable equipment such as personal protective equipment (PPE), specifically N95 masks and surgical 3 ply masks, and other items makes the HCWs vulnerable to transmission of infection while caring for these patients. Therefore, resterilization of such items has assumed equal importance. Cleaning, the first step in the process of sterilization, is of vital importance to reduce bioburden. The type of disinfection required depends on the nature of the equipment and its intended use. For example, critical items need high-level decontamination. In this narrative review, we elaborate on the methods of decontamination and sterilization. Many chemicals can be used for both sterilization and disinfection, and the difference lies in the concentration of the chemical and exposure time. We have also summarized strategies which can be used for resterilization of single-use items, in view of the shortages caused by the current pandemic.

Keywords: Chemical methods of sterilization, COVID-19 pandemic, Disinfection, Physical methods of sterilization, Personal protective equipment, Resterilization, Reuse, Sterilization.

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Introduction

Disinfection, sterilization, cleaning and maintenance of asepsis are extremely important for health care workers (HCWs), particularly in the intensive care units (ICUs) and operating rooms. This helps in preventing transmission of infections to patients and protecting HCWs, not only every day, but also during outbreaks and pandemics. Nonadherence to established guidelines can cause outbreaks of infection and has adverse impact on outcomes.[1]

In pre-coronavirus disease 2019 (COVID-19) era, single use (disposable) items were resterilized and used due to cost constraints in the low-income countries. During the current pandemic, due to the upsurge in the number of patients, the developed world is forced to resterilize single-use items (Fig. 1).

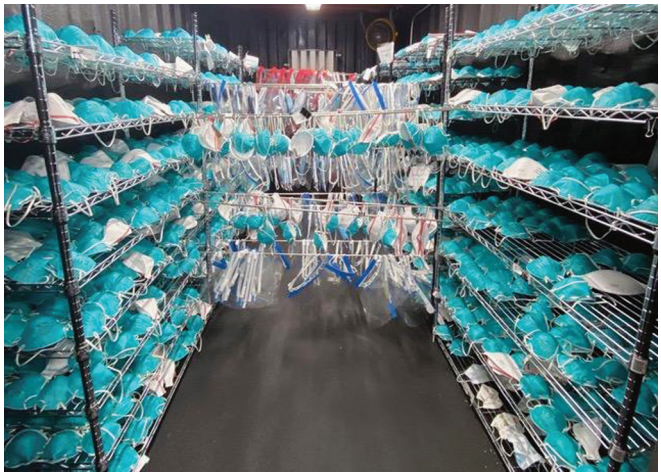

Fig. 1: A giant sterilizer machine that can sterilize up to 80,000 respirator masks per day

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In this narrative review, we discuss sterilization of equipment and disinfection of environmental surfaces, and strategies for the reuse of disposable items. For further in-depth understanding, the reader is referred to a review by McDonnell et al.[2]

Understanding the Concepts of Cleaning, Bioburden, Disinfection, Sterilization, and Asepsis

Bioburden is the number of microorganisms present on the surface before disinfection or sterilization. Biological byproducts of patients, e.g., upper and lower respiratory tract secretions, saliva, feces, and urine, can potentially transmit infections.

Cleaning is a process of reducing the bioburden by the physical removal of organic matter, involving washing (with soap and cold water) and scrubbing (mechanical action).

Disinfection eliminates many or all microorganisms, except some bacterial spores. It is further classified into high-, intermediate-, and low-level disinfection.

Sterilization destroys or eliminates all forms of microorganisms including bacterial spores. (Details below).

Asepsis ensures maintenance of the sterility of the already sterilized products or equipment. By itself, it does not ensure sterility, if sterilization is flawed.

McDonnell described a triad of human safety, machine compatibility and agent efficacy for disinfection or sterilization process, which can be adapted for HCWs.

Categories of Hospital Equipment

Spaulding classified all hospital equipment into three categories based upon their intended use.[4] These categories depended on the risk of infection, nature of exposure to tissues and meticulousness of the sterilization, and disinfection.

Critical Items[5,6]

These are used in the sterile tissues or the vascular system. These are surgical instruments, cardiac, vascular and urinary catheters, pressure transducers, implants, and various needles. They need complete sterility before use, and hence, they are either sterilized (e.g., steam sterilization for surgical instruments) or procured as sterile single-use devices (needles or catheters). Equally important is the maintenance of asepsis during their use.

Semicritical Items

These are exposed to intact mucous membranes or nonintact skin, but do not ordinarily break the tissue barrier, hence pose an intermediate risk. The tissues are susceptible to infections produced by bacteria and viruses but are resistant to infection caused by bacterial spores, so sporicidal sterilization is not required. These include breathing systems, laryngoscope blades, fiberoptic endoscopes, etc. A high-level disinfection (HLD) is mandatory for these items.

Noncritical Items

These include blood pressure cuffs, pulse oximeters, electrocardiography (ECG) cables and electrodes, and patient surroundings such as furniture and floors that are in touch with intact skin. The risk of transmission of the infections to patients with these items is very low, but they should not be exposed to nonintact skin (pressure sore, skin abrasions, etc.). These need either intermediate-level or low-level disinfection based on the bioburden. It is important to remember that incorrect method or inadequate sterilization/disinfection can expose both the patient and the HCWs to the risks of infection. On the other hand, unnecessary high level of sterilization/disinfection wastes resources and reduces the life of the equipment.

It is vital to always follow the manufacturer's recommendation for disinfection, sterilization, and cleaning. The use of incompatible methods voids the warranty and can permanently damage the equipment beyond repair and, thus, worsen the supply shortage. For example, the use of alcohol-based disinfectants for disinfection of ultrasound probes can cause permanent damage to the probes due to its reaction with the rubber head of the transducer.[7] The methods for sterilization and disinfection for the routinely used equipment in ICU and operation theater (OT) are given in Table 1.

Cleaning

This is the first and key step during the decontamination process. Disinfection or sterilization is not effective unless the equipment is completely cleaned. If possible, the equipment should be dismantled. A temperature above 45°C causes coagulation of the proteinaceous material (which forms a protective layer), making removal of microorganisms difficult and should be avoided. Cleaning should be done in a separate room to prevent potential exposure to patients and HCWs.

Automated methods for cleaning, such as washer disinfectors, low-temperature steam, and ultrasonic baths, can be used to avoid exposure of the HCWs to the chemicals and microorganisms. Manufacturer's recommendations should be followed while using automated methods.

Sterilization

Sterilization can be done by physical or chemical methods. Steam under pressure, dry heat, ethylene oxide (EtO) gas, gas plasma, and liquid chemicals like glutaraldehyde are the principal sterilizing agents used in healthcare. The key features of different methods of sterilization are summarized in Table 2.

Other Chemicals Used for Sterilization and Disinfection[2]

The key features of other chemicals used in healthcare are enumerated in Table 3.

Quaternary Ammonium Compounds

Quaternary ammonium compounds are cationic surfactants, with wide antimicrobial spectrum including bacteria, enveloped viruses like human immunodeficiency virus (HIV) and Hepatitis B virus (HBV). Quaternary ammonium compounds kill microorganisms by adsorption, penetration, and destruction of cytoplasmic membrane and cell wall and by degradation of proteins and nucleic acids. They are sporostatic at low concentrations (0.5–5 mg/L) and do not act against nonenveloped viruses but are microbiocidal at higher concentrations (10–50 mg/L).[28,29] Quaternary ammonium compounds of different generations have been used; the first generation being benzalkonium and alkyl chains, and the latest 7th generation is Bis-QACs with polymeric QACs.

Peracetic Acid[30]

Peracetic acid is a high-potency biocidal oxidizer with a similar mechanism of action to other oxidizing agents. It releases free oxygen and hydroxyl radicals leading to microbiocidal effects against bacteria (including mycobacterium) and bacterial spores, fungi, and viruses (poliovirus, rotavirus, HBV, and HIV) rapidly (<10 minutes). It acts by denaturation of proteins, disruption of cell wall permeability, oxidization of sulfhydral and sulfur bonds in proteins, enzymes, etc. Its constituents are acetic acid and H_2O_2. In the concentrated form, peracetic acid is corrosive and irritating. It is available as 0.2% and 0.35% solutions. It is safer but costlier than glutaraldehyde, and in the future, after further trials, it may be an alternative to glutaraldehyde.

Ultraviolet (UV) Radiation or Ultraviolet Germicidal Irradiation (UVGI)[31,32]

Ultraviolet germicidal irradiation (UVGI), which damages the microbial nucleic acid, has been used for the disinfection of titanium

Table 1: Sterilization/disinfection of routinely used equipment in ICU and ORs

Categories of hospital equipment	*Item*	*Preferred method*	*Alternative method*
Semicritical	Steel laryngoscope blades[8]	Cleaned with cool running tap water. Immersed in disinfectant solution as per manufacturer's recommendations (glutaraldehyde, hydrogen peroxide, ortho-phthalaldehyde, and peracetic acid with hydrogen peroxide 1% sodium hypochlorite or alcohol-based disinfectants) for a minimum of two minutes and rinsed with lukewarm running tap water. Brushed in enzymatic detergent and rinsed again in reverse osmosis (RO) water to remove detergent residuals. Dried with a lint-free cloth or filtered pressurized air. The bulb may be cleaned with a cotton ball dampened in alcohol (IPA), 1% sodium hypochlorite or alcohol-based disinfectants	Autoclave
	Video laryngoscope blades	Plasma sterilization 70% IPA Wipe[9] Ethylene oxide (EtO) gas[10]	
	Silicone face mask and manual resuscitator bag[11]	Disassemble and rinse parts under cold running water. Submerge all parts in water containing dish washing detergent at 60–70°C and clean with brush Cidex OPA (ortho-phthalaldehyde) 0.55% solution for 60 minutes Or sodium hypochlorite 0.5% solution for 20 min	Autoclave
	Silicone breathing systems (circuits) of ventilators[12]	Autoclave or chemical disinfection as per manufacturer's recommendation	ETO (banned in some countries)
	Oral thermometers	1% sodium hypochlorite or alcohol-based disinfectants	
	Temperature probes		
Noncritical	ECG cable	1% sodium hypochlorite or alcohol-based disinfectants	
	Pulse oximeter[9]	Cleaning with alcohol solution Disinfection with glutaraldehyde solution: 2.0%	1:10 bleach CIDEX OPA if HLD is required
	Axillary thermometers	Wash with cool water 1% sodium hypochlorite or alcohol-based disinfectants	
	Stethoscopes	70% isopropyl alcohol solution	
	Plastic blood pressure cuffs	0.5% hydrogen peroxide	
	Cloth blood pressure cuffs	Remove the tubing and inflation bag. Wash cuff with soap water	
	Ultrasound probe[13]	Alcohol-free quaternary ammonium wipes	Sodium hypochlorite wipes
Environmental surfaces	Ventilator screen[9]	Isopropyl alcohol (70% solution) Bleach (10% solution)	
	Anesthesia workstation	Disinfection as per manufacturer's recommendation	Can be covered with sterile plastic sheet which can be changed between two cases
	Monitor screen[14]	Cleaning with a lint-free cloth, moistened with warm water (40°C) and soap, a diluted noncaustic detergent, ammonia- or alcohol-based cleaning agent Disinfection with ethanol 70%, isopropanol 70%, or Cidex-activated dialdehyde solution	Do not use bleach
	Ultrasound machine[13]	Covering with plastic sheet to change between the patients	Alcohol-free quaternary ammonium wipes

Table 2: Commonly used sterilization techniques in health care

Technique	*Process*	*Mechanism of action*	*Uses*	*Advantages*	*Disadvantages*
Steam sterilization	121°C for 15 minutes or 134°C for 3 minutes	Denaturation and coagulation of enzymes and structural proteins	Surgical instruments can be used for stainless steel laryngoscope (battery removed)	Safe to patient, HCWs and environment Low cost Can work in the presence of moisture	Damage to heat-sensitive equipment Loss of sharpness (needles, etc.)
Ethylene oxide (EtO) gas sterilization[15]	Concentration of 450–1200 mg/L, at temperatures of 37 to 63°C and RH of 40 to 80% for 1 to 6 hours	Alkylation (replacement of a hydrogen atom with an alkyl group) of microbial proteins, DNA and RNA	Heat-sensitive equipment and instruments Disposable catheters and guidewires	Can sterilize heat- or moisture-sensitive medical equipment	Moderate cost, prolonged cycle time Potential toxicity to patients, HCWs, and environment Banned for use in respiratory equipment in some countries
Hydrogen peroxide vapor (HPV) and hydrogen peroxide gas plasma (HPGP) sterilization[16]	Concentration of 6 mg/L, temperature range of 37–44°C Cycle time of 75 minutes	Hydroxyl [·OH, the neutral form of the hydroxide ion (OH−)] and hydroperoxyl (HO_2·)-free radical and gas plasma formation	Heat-sensitive equipment and instruments	Low-temperature sterilization Safe to patient, HCW, and environment	High cost Does not work in the presence of moisture, cellulose, or cotton. Poor penetration due to condensation at surface[17]

HCWs, healthcare workers

implants, contact lenses, etc. Its maximum bactericidal effect occurs at 240–280 nm (UV-C). Mercury vapor lamps are commonly used as they emit radiation at 253.7 nm.

Upper-room UVGI provides disinfection of the upper part of air in the room and can be used in the occupied rooms without using protective clothing. Effective air disinfection in the lower part of the room depends on vertical air movement. There is a lack of data supporting its use in isolation rooms. It can cause occasional skin erythema and keratoconjunctivitis in patients and visitors. The use of UVGI for the decontamination of masks [filtering face piece respirators (FFRs)] is described below in detail.

Disinfection[1]

Disinfection can be classified into high-, intermediate-, and low-level disinfection. While sterilization mandates prolonged exposure, disinfection needs shorter exposure. These terms are not interchangeable.

High-level Disinfection

It destroys all microorganisms but not bacterial spores. Many chemicals can be used for disinfection (glutaraldehyde, hydrogen peroxide, etc.) with exposure times varying from 8 to 45 minute, at 20 to 25°C. They can be used for sterilization when used for prolonged period. High-level disinfection is mainly used for semicritical items.

Intermediate-level Disinfection

It destroys all microorganisms but spares spores and some small nonenveloped viruses. Intermediate-level disinfection is used for noncritical items, which are visibly soiled with patient's fluids and blood. This is done with alcohol or QACs, etc.

Low-level Disinfection (LLD)

It destroys most microorganisms and some viruses but has no action on *Mycobacterium tuberculosis* and spores. Low-level disinfection can also be achieved with alcohol or QACs, etc., at lower exposures. Low-level disinfection is used for noncritical items.

Surface Contamination and Transmission of COVID-19 Infection

Transmission of the SARS-CoV-2 virus can occur directly between humans and indirectly through contact with surfaces or objects.[33] It remains viable in the surroundings of the infected person. The viability of the virus depends on bioburden, ambient temperature, relative humidity (RH), and pH. In the areas surrounding even stable COVID-19 patients, there is high likelihood of contamination of environmental surfaces and ICU furniture, including common electronic equipment, e.g., telephones, computers, etc. It is therefore vital that all surfaces are frequently cleaned and disinfected.

Viability of SARS-CoV-2 in Various Environmental Conditions[34,35]

SARS-CoV-2 virus can survive up to seven days at room temperature (22°C) with a RH of 65% on stainless steel and plastic surfaces, indicating possible fomite transmission. It is extremely stable over a pH of 3–10. Viable virus can still be present on the outer layer of a surgical mask on the seventh day. It becomes nonviable on cardboard in 24 hours.[36] On copper surfaces, it becomes nonviable within 4 hours. Soap solution (1:49) did not achieve effective virucidal effect.

Current Recommendations for Sterilization and Disinfection of Medical Equipment and Environment

The selection of disinfectants should be based on various factors such as targeted microorganisms, availability of disinfectants, etc.

Table 3: Commonly used chemical disinfectants in health care

Chemical, concentration used	*Uses*	*Caution/limitation*
Alcohols Ethyl alcohol (ethanol, alcohol) and isopropyl alcohol, 60 to 90%; use of higher concentrations leads to quick evaporation and reduced contact time[18]	Environmental surface cleaning (recommended for COVID-19) Disinfection of oral and rectal thermometers, hospital pagers, scissors, and stethoscopes. Rubber stoppers of multiple-dose medication vials or vaccine bottles Surface cleaning	No sporicidal activity Concentrations less than 50% have poor antimicrobial activity Avoid exposure to face visor, goggles, and ultrasound probes
Halogen-releasing agents: *Hypochlorite solutions*: 0.1% (1000 parts per million/ppm) for surface cleaning Higher concentration of 0.5% (5000 ppm) for large (>10 mL) spills of blood and body fluids and *C. auris* and *C. difficile*[19]	Environmental surface cleaning (recommended for COVID-19) Sporicidal activity present but not commonly used for sterilization[20]	Irritation of eyes, skin, and mucous membrane Avoid exposure to persons with reactive airway disease like asthma Cause corrosion of metal. Fresh dilution should be prepared daily Solution should not be exposed to direct sunlight or kept open for long time
Hydrogen peroxide >0.5%[18]	Environmental surface cleaning (recommended for COVID-19) It can enhance the removal of organic matter and organisms, hence also used for washing of wounds	Irritation of eyes Organisms with high cellular catalase activity such as *Staphylococcus aureus*, *Serratia marcescens*, and *Proteus mirabilis* are relatively resistant and require nearly an hour of exposure No need for daily fresh preparation Solution should not be exposed to direct sunlight or kept open for long time.
Glutaraldehyde 2% (Cidex®) for 20 minutes,[21] or ortho-phthalaldehyde (Cidex®OPA) 0.55% for 12 minutes[22]	Disinfection of optical instruments such as cystoscopes or bronchoscopes For sterilization, exposure as long as >10 hours is required.[5] Noncorrosive and has no deleterious effects on lens cement	Meticulous cleaning to remove organic matter Prior leak test Avoid ortho-phthalaldehyde for urological instruments
Halogen-releasing agents iodine and iodophors[20,23]	Skin preparation Nasal spray and mouthwash for patients to protect HCWs[24]	Should not be used on silicone catheters[18]
Chlorhexidine impregnation or 0.2% aqueous solution[25]	Vascular catheters, needleless connectors, and antimicrobial dressings, gargles or mouthwash.	Poor action against coronaviruses, nonenveloped viruses, mycobacteria Maximum bactericidal effect occurring within 20 seconds
Chlorhexidine 2% in 70% alcohol 0.5% in 70% alcohol	Preprocedural skin preparation\Skin preparation for central neuraxial blockade.[26] (2% in 70% alcohol) Hand disinfectant (0.5% in 70% alcohol)	Efficacy comparable with that of 10% povidone-iodine solution[27]
Quaternary ammonium compounds: up to 7th generations available). See text for the mechanism of action[28]	Environmental sanitation of noncritical surfaces, such as floors, furniture, and walls[18]	Effective dose of the QACs is compromised if used with cotton mops or cleaning towels Better to use wipes and follow manufacturer's recommendation.

The persons preparing and using the disinfectant solution should be protected using the appropriate PPE.

Disinfection of Environmental Surfaces[19]

Most disinfectants get rapidly inactivated in the presence of organic material. Hence, it is important to clean the surface with soap water or detergent and mechanical action. The following disinfectants are recommended for disinfection of environmental surfaces in healthcare settings.

- Ethanol 70–90% (higher concentrations lead to quick evaporation with reduced contact time)
- Chlorine-based products (e.g., hypochlorite) at 0.1% (1,000 parts per million/ppm) for general environmental disinfection or 0.5% (5,000 ppm) for large spills of blood and other fluids
- Hydrogen peroxide >0.5%

When the disinfectants are used on surfaces in recommended concentration, for appropriate duration, they achieve a >3 $\log_{10}$ (99.9%) reduction of coronaviruses[20] (Table 4).

Terminal and Concurrent Disinfection

Terminal cleaning is the disinfection and sterilization of patient supplies and equipment after patient discharge, while concurrent cleaning is the disinfection and sterilization during hospitalization. Some countries use vaporized hydrogen peroxide or ultraviolet (UV) irradiation for terminal disinfection. If either technique is used,

Table 4: Cleaning and disinfection of environmental surfaces: recommended schedule and methods[19]

Item	*Frequency of disinfection/sterilization*	*Recommended methods*	*Comments*
Common areas	At least twice daily, preferably three times daily	Any one of the following with contact time of at least 1 minute • Ethanol 70–90% • Hypochlorite 0.1% (0.5% for blood and body fluids large spills) • Hydrogen peroxide >0.5%	Cleaning should progress from the clean to dirty area. Surfaces, which are frequently touched, are considered dirty As debris may fall down from higher areas should be cleaned before lower areas and floor should be cleaned at last Preferably use new cloth for each bed. Fogging or spraying of disinfectants should be avoided
In-patient rooms occupied with patient	Three times daily		For equipment, compatibility with chemical disinfectant should be checked
Bathrooms/toilets	At least three times daily for shared toilets At least twice daily for individual toilet		
In-patient rooms after patient discharge (terminal cleaning)	After every patient discharge		Additionally, fogging or spraying disinfectants preferably with no-touch technique can be used

it should supplement and not replace the manual cleaning and disinfection using ethanol, hypochlorite, or hydrogen peroxide. The supplemental methods (vaporization or irradiation) should be used only with the room empty.

Methods Not Recommended for Disinfection[19]

Spraying individuals with disinfectants (in a tunnel, cabinet, or chamber) does not reduce an infected person's ability to spread the virus and can be harmful to the individuals due to toxic chemicals. World Health Organization does not recommend spraying or fogging with chemicals in indoor spaces due to its adverse health effects on HCWs. Similarly, spraying or fumigation of outdoor spaces is not useful at its best and can be harmful to individuals, at its worst.

Reuse of Disposable Items

We must emphasize here that if adequate PPE is available, resterilization and reuse should not be carried out solely to save money. Due to overwhelmed healthcare systems, and shortage of disposables, we need to decontaminate and resterilize PPE but maintain its functionality. For the methods of sterilization/decontamination for reuse of items which form the part of PPE, see Tables 5 and 6.

Disposable Face Shields and Goggles[37]

These are first wiped with neutral detergent solution using clean cloth or rinsed if needed and cleaned with 0.1% hypochlorite solution. Alcohol is avoided as it can damage and discolor plastic.

PPE Suit and Three-ply Surgical Mask[46]

Single-use disposable PPE suits and three-ply surgical masks are manufactured from the heat-sensitive material and should not be resterilized. While PPE protects an individual when it is being worn, incorrect technique of removal (doffing) and incorrect disposal of contaminated PPEs can expose the wearer and other people to virus. Hence, proper doffing and disposal is key to prevent exposure. If reusable PPE suit is available, care should be taken during doffing, cleaning, and repacking for sterilization. It is highly desirable to use PPE suit that has undergone quality control testing and is certified by competent authorities like National Institute for Occupational Safety and Health (NIOSH).

N95 Filtering Face Piece Respirators (FFRs)[47]

The following points must be considered for decontamination:

- Virucidal effect of disinfection method: measured as log reduction in viral load (three $\log_{10}$ reduction indicates reduction in viable virus number by 1,000 times).
- Quality of filter: The filter resistance should not increase as it makes it hard to breathe. At the same time, the filter should block at least 95% of airborne particles.
- Mask fitting: There should not be a significant change in the shape of mask, and the elastic quality of the strap should be maintained to allow tight fit. This is tested using smoke or fragrance ideally. The wearer should not be able to smell it, if the mask fit is good. Detailed procedure for the assessment of mask-fit is beyond the scope of this article. Readers are referred to the Occupational Safety and Health Standards recommendations.[48]

Mask Rotation

One simple strategy, not requiring sterilization, is to issue five such N95 respirators to each HCW on the first day. These can be numbered and one FFR is used every day. At the end of each shift, the respirator is carefully removed (considering it is contaminated) and stored in a breathable paper bag. The virus is unlikely to survive after 72 hours; hence, the first mask can be safely reused on the sixth day. Additionally, they should wear a three-ply mask over FFR to protect it from contamination. Face shield over the disposable respirator prevents surface contamination.[49]

UK government recommends folding the mask to keep the outer surface inward and against itself and to reduce likely contact with the outer surface during storage in a clean sealable bag/box marked with the person's name and stored in a well-defined place.[50]

Table 5: Current methods for sterilization/decontamination for reuse of various items constituting PPE

Item	*Recommended method of sterilization*	*Additional comments*
Single-use N95 filtering face-piece respirators (FFRs)	Highly recommended methods • Hydrogen peroxide vapor • Moist heat 65 ± 5°C and 50–80% RH for 30 minutes Less recommended • UV germicidal irradiation Alternate method of decontamination Mask rotation: storage in a breathable paper bag and reuse on sixth day (see Table 6 for details)	Hand hygiene during doffing, repacking, and donning of FFR. Following methods should be avoided • Cleaning with soapy water, detergent, or disinfectants • Sterilization using steam or EtO • Use of alcohol or household bleach
Disposable face shield[37]	Cleaning with cloth saturated with neutral detergent solution	Following methods should be avoided
	Wiping with chlorine-based disinfectant (0.1% chlorine solution)	Cleaning with alcohol can damage or discolor shield
Three-ply surgical mask	None	NOT FOR REUSE
Single-use disposable PPE	None	NOT FOR REUSE
Reusable elastomeric half and full face-piece respirators[38]	Resterilized as per manufacturer's recommendations, e.g., cleaning or disinfection of disk-style filters and prefilter pads is not recommended.	
	Hard-plastic case surrounding the filter media can be disinfected with either sodium hypochlorite solution (0.5%) or 70% isopropanol with 1-minute contact time	
Reusable PPE suit	Resterilized as per manufacturer's recommendations	Avoid exposure during doffing, cleaning, and repacking for sterilization
Reusable goggles or face shield	Resterilized as per manufacturer's recommendations	Avoid exposure during doffing, cleaning, and repacking for sterilization

If adequate PPE is available, resterilization and reuse should not be carried out solely to save money

While donning the FFR and performing a seal check, a pair of clean nonsterile gloves should be used.[51] Degesys et al. demonstrated high failure rate of used duckbill-shaped (Kimberly-Clark 46727 and Halyard 46867) N95 FFR in relation to the mask-fit.[52]

Mask Reprocessing/Decontamination

Typically, HCW uses his own FFR for repeat use. The FFRs, which are soiled, damaged, or hard to breathe with, should be immediately discarded. FFR used during aerosol-generating procedures or close contact with the infected patients requiring contact precautions should be discarded.[51] Tie-on masks, difficult to remove without damaging, are discarded. Most FFRs have elastic ear hooks and can be considered for reuse. It is prudent to perform hand hygiene before removing the facemask and after keeping it in the designated place. Procedures for resterilization of contaminated FFRs and the supporting evidence are summarized in Table 6.

Centers for disease control and prevention (CDC)-approved methods for decontamination are vaporous hydrogen peroxide (HPV), UVGI, and moist heat sterilization.[53] Some institutes in the United States are using hospital-grade UV treatment.[54] Household UVGI sterilization cabinets are NOT RECOMMENDED for use.[55] Ozone is another promising method for sterilization.[46] It has faster virucidal action and causes slower degradation of FFR. Unlike UVR, ozone easily reaches the crevices of mask. Previously, ozone in concentration of 27.73 mg/L was shown to inactivate SARS-CoV-1 virus within four minutes.[56] In summary, disposable N95 FFR can be resterilized by hydrogen peroxide vapor, UV radiation, moist heat, dry heat, and ozone gas. Methods such as soap water, alcohol, bleach immersion, EtO, ionizing radiation, microwave, high temperature, autoclave, or steam should be avoided.[46]

Quality Control[5]

The process of sterilization can be monitored with various mechanical, chemical, and biological indicators which ensure compliance to specific conditions of the sterilization process. However, they do not confirm sterility. Thermometers can be used to record the temperature of the sterilization cycle. Chemical indicator tapes change color and can distinguish sterilized packets from the one which are yet to be processed. Biological indicators in the form of nonpathogenic spore-forming heat-resistant bacteria are most accurate for checking sterilization effectiveness. Disinfectants concentrations (e.g., chlorine percentage in hypochlorite solution) can be checked if facilities are available. It is preferred to use certified consumables. Visual inspection is not a reliable method of assessment of cleanliness. Ultraviolet marker pens can be used to make marks on the surfaces, which are frequently touched, known as "high-touch objects." These marks are not seen with the visible light but are fluorescent under a near-UV light known as black light. These fluorescent marks disappear with cleaning and hence can be used to monitor sustained improvement in cleaning.[57,58]

Table 6: Decontamination and sterilization methods for N95 FFR

Author, year	*FFR tested*	*Methods compared*	*Results*
Viscusi, 2007[39]	N95, P100	Tap water (control)	H_2O_2, VHP, UV radiation, and dry heat 80°C caused the least change in the filtration performance
		Liquid decontamination methods	Dry heat, microwave, and EtO increased the penetration levels but were in the limits
		1. H_2O_2 Fisher 30% stabilized	Autoclave, IPA, and soap and water significantly degraded the performance of filter
		2. Bleach; Fisher 5.25% sodium hypochlorite (NaOCl) with 0.20% sodium hydroxide (NaOH)	
		3. Isopropyl alcohol (IPA), 70%	
		4. Ivory bar soap 1g/L	
		UV radiation (0.24 mW/cm^2)	
		Dry heat (oven)	
		Microwave (26 mW/cm^3)	
		Autoclave 121°C (15 psi)	
		EtO	
		Vaporized hydrogen peroxide (VHP)	
Viscusi 2009[40]	N95 FFR surgical N95 respirators (splash resistant) P100 FFRs	UVGI 15-minute exposure to each side (outer and inner), 176–181 mJ/cm^2 exposure to each side of FFR.	UVGI, EtO, and VHP did not affect the filter aerosol penetration, filter airflow resistance, or physical appearance
		EtO	Some degradation of metallic band with bleach and VHP
		VHP	
		Microwave oven irradiation	Microwave oven irradiation (melting) and bleach decontamination methods (chlorine smell) were least desirable
		Bleach 30 minutes submersion in 0.6%	
Bergman 2010[59]	Three N95 FFR and three surgical N95 FFR	UVGI	Three-cycle treatment of UVGI, EtO, and HPV had no effect on the filter performance.
		EtO	HPGP caused increase in filter aerosol penetration to >5%.
		HPGP	
		HPV	MGS and MHI caused partial separation of the inner foam nose cushion from the FFR
		MGS	
		Bleach 30-minutes submersion in 0.6%	Bleach caused oxidation, discoloration of mask, and chlorine smell
		H_2O_2 30-minutes submersion in 6%	
		Moist heat incubation/pasteurization (MHI) 30-minutes incubation at 60°C, 80% RH	LHP caused oxidization of staples
Fisher 2010[60]	Cardinal N95-ML	Biological safety cabinet UVGI	Minimum dose required for 3 log reduction: 1000 J m)2
	Wilson SAF-T-FIT_ Plus 3M 8210, 1860 and 1870 Kimberly-Clark PFR95-174		Variable time required between 2 and 266 minutes depending on the FFR
Heimbuch 2011[41]	Particulate and surgical FFR	MGS1250 W 2 minutes	More than 4-log reduction of viable H1N1 virus with all three techniques
		Warm moist heat (WMH) 65°C 85% RH for 30 minutes	
		UVGI (254 nm) 1.6-2.0 mW/cm^2 15 minutes	
Lore 2012[42]	3M 1860 and 1870 FFR	UVGI (254-nm wavelength) lamp	More than 4-log reduction of viable virus
		MGS 1250-W moist heat	No significant degradation of the filter performance at 300-nm particle size
Bioquell 2016[43] (Not endorsed by FDA)	3M 1860 FFR	HPV	Exposure to up to 50 HPV cycles did not degrade the filtration media with respect to inert and bioaerosol collection efficiency and filtration resistance
			Exposure to up to 20 cycles caused degradation of elastic straps

Contd…

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Author, year	*FFR tested*	*Methods compared*	*Results*
			Mask fit was acceptable till 20 cycles, after that it could not be tested due to strap degradation
Lindsley 2015[61]	3M 1860, 9210 GE 1730 KC 46727	UVGI 254 nm (UV-C) at various exposure 0, 120, 240, 470, or 950 J/cm^2 on each side	Small, up to 1.25% increase in particle penetration Little effect on the flow resistance Less effect on the respirator straps
Heimbuch, B.K 2019[44]	3M 1870, 1860, 1870 N95 FFR, VFlex 1805, Kimberly-Clark PFR, Moldex 1512, 1712, EZ-22, Precept 65-3395, Gerson 1730, Sperian HC-NB095, U.S. Safety AD2N95A, AD4N95, Alpha protech 695, Prestige Ameritech RP88020, Sperian HC-NB295F	UVGI dose of 1 J/cm^2 in a 360° orientation around an FFR	All 15 FFR models tolerated up to 20 cycles of UVGI treatment without significant effect on, fit, air flow resistance, or particle penetration. Straps of 3M 1860, 3M 1870, and Kimberly-Clark PFR models tolerated 10 cycles but degraded after 20 cycles All FFR models demonstrated >3 log reductions on mask with exception of Gerson 1730, Sperian HC-NB095, U.S. Safety AD2N95A, 3M VFlex 1805, and Precept 65-3395 models. Decontamination of strap was poor. The models with >3 log reductions on straps for both soiling agents were the Sperian HC-NB095, Kimberly-Clark PFR, Precept 65-3395, and Prestige Ameritech RP88020.
Liao 2020[45]	3M 8210	Dry heat (75°C)	No degradation with
	4C Air ESound	Steam	• 50 cycles of 85°C heat at 30% RH
	Onnuriplan	Ethanol (75%)	• 20 cycles with dry conditions with temperatures up to 100°C
	Melt blown fabric (Guangdong Melt-blown Technology Co)	Household diluted chlorine-based solution (2%) UVGI (254 nm, 8 W)	• 10 cycles with UV irradiation Significant reduction in filtration Efficiency with ethanol and household diluted chlorine-based solution

If adequate PPE is available, resterilization and reuse should not be carried out solely to save money
UVGI, ultraviolet germicidal irradiation; HPV/VHP: hydrogen peroxide vapor; MGS, microwave-generated steam; EtO, ethylene oxide; H_2O_2, hydrogen peroxide; HPGP, hydrogen peroxide gas plasma

Summary

Prevention of transmission of infectious diseases to patients and healthcare workers is a top priority, particularly during the pandemic. Healthcare workers should understand the criticality of the equipment and also the concepts of bioburden, sterilization, disinfection, cleaning, and Asepsis. Checking compatibility of the "anti"-COVID methods of sterilization/disinfection with the equipment (based on manufacture's recommendation) avoids damage to the equipment and ensures its longevity. Environmental surface decontamination is an important strategy during COVID-19. The reuse of single-use PPE like disposable face shield N95 FFRs is possible, provided the recommendations are followed stringently. Resterilization of single-use (PPE) suit and three-ply surgical mask should be avoided due to the presence of heat-sensitive material and lack of evidence suggesting appropriateness of its sterilization/decontamination.

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