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INTRODUCTION

The pneumonia associated with novel coronavirus disease 2019 (COVID-19 or nCoV) may lead to respiratory failure with profound hypoxemia requiring endotracheal intubation and mechanical ventilation. The rapidly spreading pandemic may result in utilization of all available intensive care unit (ICU) ventilators in individual institutions and regions. Repurposing of anesthesia machines for longer-term use for days or weeks to ventilate COVID-19 patients or other patients requiring mechanical ventilation has been proposed, but is somewhat unprecedented. Furthermore, anesthesia machines have only been rarely used to administer inhalation anesthetics during prolonged ventilation.

This topic will address management of short-term or long-term intensive care ventilation with an anesthesia machine, emphasizing this use for patients with COVID-19 pneumonia [1]. Airway management and anesthetic care of patients with suspected or confirmed diagnosis of COVID-19

infection for surgical procedures, including preventing infection of anesthesia personnel or contamination of anesthesia machines and equipment are addressed in a separate topic. (See "Coronavirus disease 2019 (COVID-19): Anesthetic concerns, including airway management and infection control".)

Use of standard ICU ventilators and ventilation of critically ill patients COVID-19 patients are discussed separately. (See "Coronavirus disease 2019 (COVID-19): Critical care and airway management issues", section on 'Ventilator management of acute respiratory distress syndrome'.)

Other details regarding obstetric and critical care of patients with COVID-19 infection, and general medical management are available in additional topics:

- (See "Neuraxial analgesia for labor and delivery (including instrumented delivery)", section on 'Patients with suspected or confirmed COVID-19'.)
- (See "Coronavirus disease 2019 (COVID-19): Critical care and airway management issues".)
- (See "Coronavirus disease 2019 (COVID-19): Management in hospitalized adults".)
- (See "Coronavirus disease 2019 (COVID-19): Epidemiology, virology, clinical features, diagnosis, and prevention".)
- (Related Pathway(s): Coronavirus disease 2019 (COVID-19): Initial telephone triage of adult outpatients.)

PREVENTION OF ANESTHESIA MACHINE CONTAMINATION

Preventing contamination of the external parts of the anesthesia machine, its breathing system and ventilator, and its connection to the gas analyzer and attached monitoring equipment while in use for patients with COVID-19 is described in another topic. (See "Coronavirus disease 2019 (COVID-19): Anesthetic concerns, including airway management and infection control", section on 'Protection of anesthesia equipment'.)

Contamination of an anesthesia machine during use as an intensive care ventilator for patients with known COVID-19 infection is more likely than use during a surgical procedure because of the duration and extent of machine exposure. Based on studies of other coronaviruses, it is estimated that infected patients exhale 0 to 100,000 virus particles per 30 minutes, or as many as 4,800,000 particles per day [2]. However, a single filter with a viral filtration efficiency (VFE) of 99.9999 percent (ie, a good mechanical pleated filter at the expiratory limb) would allow 4.8 of these particles, on average, to pass. If two filters are used such as a heat and moisture exchange filter (HMEF) containing an electrostatic filter placed at the airway plus a mechanical pleated filter placed at the expiratory limb of the breathing circuit (figure 1), the combined VFE is very high (perhaps as high as 99.99999999 percent), rendering contamination of the anesthesia machine unlikely, even when

used for multiple days (with fresh filters each day). (See "Coronavirus disease 2019 (COVID-19): Anesthetic concerns, including airway management and infection control", section on 'Contamination of the internal components of the anesthesia machine'.)

LOCATIONS FOR ANESTHESIA MACHINES

Location(s) selected for use of anesthesia machines to ventilate COVID-19-positive patients will be institution-dependent due to considerations such as layout of selected hospital area(s), location of rooms with negative pressure capabilities, and availability of sources of electrical power, high-pressure oxygen, and medical air [1,3]. Personnel considerations include availability of anesthesia personnel to manage ventilation with anesthesia machines, and convenience for critical care consultants. When multiple anesthesia machines are used in a single location, the compressed gas pipelines should be assessed to ensure that supply is adequate to meet consumption if supplying an area where multiple anesthesia ventilators are using high fresh gas flows (FGFs). The electrical supply should also be assessed to ensure that circuits will not be overloaded, particularly in areas outside the operating room (OR).

Availability of compatible connections from the scavenger system to waste anesthesia gas disposal outlets or medical vacuum outlets is another necessary consideration if inhalation anesthetic agents are to be administered using the anesthesia machine. However, gas scavenging is not necessary if inhalation agents are avoided. (See 'Differences between anesthesia machine ventilators and ICU ventilators' below and 'Use of inhalation anesthetics for sedation' below.)

Institutional options for location of anesthesia machine ventilators may include intensive care unit (ICU) rooms, the presurgical holding area, post-anesthesia care units (PACUs), or individual ORs [1]. In some institutions, it may be possible to treat two or more COVID-19 patients in the same OR if there are multiple sources of oxygen and medical air, and if anesthesia personnel (ie, anesthesiologists, Certified Registered Nurse Anesthetists [CRNAs], Certified Anesthesiologist Assistants [CAAs]) are deployed most easily in an OR setting. Notably, the American Society of Anesthesiologists (ASA) and the Anesthesia Patient Safety Foundation (APSF) guidelines for repurposing of anesthesia machines for longer-term ventilation recommend that anesthesia professionals be immediately available at all times to manage and monitor the anesthesia ventilator (and administration of inhalation anesthetic agents, if used), as well as to assist with respiratory care (refer to the APSF/ASA Guidance on Purposing Anesthesia Machines as ICU Ventilators and Quick Reference: Setup and Monitoring Instructions – Anesthesia Machine as an ICU Ventilator), regardless of the locations(s) for the anesthesia machines [4,5]. (See 'Monitoring long-term ventilation' below and 'Monitoring during sedation with inhalation anesthetics' below.)

LONG-TERM VENTILATION WITH ANESTHESIA MACHINES

The American Society of Anesthesiologists (ASA) and the Anesthesia Patient Safety Foundation (APSF) have developed guidance for anesthesia care team members regarding repurposing of anesthesia machines for longer-term ventilation (refer to the APSF/ASA Guidance on Purposing Anesthesia Machines as ICU Ventilators and Quick Reference: Setup and Monitoring Instructions – Anesthesia Machine as an ICU Ventilator) [4,5]. These professional societies recommend that anesthesia professionals be immediately available at all times to manage and monitor the anesthesia ventilator. Professional staff who are not anesthesiologists (eg, some intensivists, as well as respiratory therapists, and intensive care unit [ICU] nurses) are experts in respiratory care, but are not familiar with anesthesia machines. Because of the increased amount of interaction required, using anesthesia machine ventilators for patients who require mechanical ventilation for a period of time, but who are **not** COVID-19-positive, may be a good option for optimal use of institutional resources.

Limited data regarding duration of mechanical ventilation for COVID-19 patients suggest that two or more weeks are often necessary. Collaboration with critical care teams throughout this period is clearly essential to achieve optimal respiratory care, and to manage other systemic problems in patients with severe COVID-19 disease. (See "Coronavirus disease 2019 (COVID-19): Critical care and airway management issues", section on 'Ventilator management of acute respiratory distress syndrome'.)

Differences between anesthesia machine ventilators and ICU ventilators — Data are limited regarding the capabilities of anesthesia machine ventilators developed by various manufacturers to mimic ICU ventilator parameters or reliably provide continuous mechanical ventilation for prolonged periods of time. Although newer anesthesia ventilators incorporate multiple controlled and assisted modes of ventilation that are nearly identical to intensive care ventilators, there are several important technical issues that are unique to anesthesia machines, which must be considered during use for long-term ventilation.

Adjusting humidification of inspired gases

- The need to adjust fresh gas flow (FGF) to prevent condensed water accumulation in the breathing circuit [3]. Intensive care ventilators deliver fresh gas during each inspiration, and discharge all exhaled gas into the room. Because compressed gases have zero humidity, active humidification is necessary. The ability to alter FGF and the fraction of exhaled gas rebreathed is a key feature distinguishing an anesthesia ventilator from an ICU ventilator. FGF is typically reduced during general anesthesia to conserve inhalation anesthetic agent. A FGF that is lower than minute ventilation increases rebreathing of exhaled gas, which has been

humidified by the body. The reaction of rebreathed carbon dioxide (CO_2) with the CO_2 absorbent produces additional humidity within the circuit. Experience to date indicates that when an anesthesia machine is in long-term use as an ICU ventilator, reducing FGF leads to excessive humidity in the breathing circuit, and the need to change CO_2 absorbent frequently (see "Anesthesia machines: Prevention, diagnosis, and management of malfunctions", section on 'Carbon dioxide absorbent exhaustion or toxicity'). This additional humidity can be clinically significant leading to water condensation within the breathing circuit that can increase resistance to gas flow through the system, interfere with sensors such as respiratory gas analyzers and flow sensors, and increase risk for coinfections [3]. For these reasons, significant accumulations of water in the breathing circuit (typically expiratory limb) must be emptied. Accumulated water should be emptied carefully and while wearing full personal protective equipment (PPE), because it may be contaminated with virus. Condensers and water traps may be added to some breathing systems to aid in managing excessive humidity [2]. Issues with supply chains have limited purchase of such water traps during the COVID-19 pandemic; however, new options have been designed and tested in some institutions [3].

To prevent buildup of humidity and decrease the use of CO_2 absorbent, it is recommended that FGF be set to equal minute ventilation initially (approximately 6 to 8 L/minute in adult patients). Generally, it should be apparent in one to two hours if excess moisture is accumulating in the breathing circuit. If it is, FGF can be increased incrementally (eg, by 0.5 to 1 L/min) until humidity is controlled. Alternately, FGF can be set higher (eg, 1.5 times minute ventilation) initially, and can then be reduced in increments of 500 mL/minute with vigilant monitoring for the appearance of humidity in the inspiratory limb. Once FGF exceeds 1.5 times minute ventilation, there is little rebreathing, and increasing FGF further does not provide any advantage and wastes compressed gas (oxygen and medical air).

- The need for long-term humidification and warming of inspired gases. Critical care patients should inspire warm humidified gases to prevent drying of secretions and respiratory epithelium. At the low FGFs typically used in the operating room (OR), inspired gas is humidified due to rebreathing [6,7], and also by the release of heat and humidity by the reaction of CO_2 with the absorbent [8]. The presence of condensate in the inspiratory hose indicates that the inspired gas relative humidity is >100 percent at room temperature.

  However, a heat and moisture exchange filter (HMEF) may be necessary when high FGFs are used to prevent condensed water accumulation during prolonged ventilation with an anesthesia machine. The HMEF should be placed at the endotracheal tube connection to the breathing circuit (after the Y-piece and the gas sampling port (figure 1)). This HMEF will ensure that adequate humidity is maintained in the lungs and will also filter viral particles.

Filters and HMEFs at the airway are prone to obstruction from moisture or secretions. Compared with the OR setting, obstruction of an airway filter or HMEF placed on an anesthesia machine breathing circuit in the ICU may be less likely to be detected early since there may not be constant attendance by an anesthesia professional. Airway filters and HMEFs should be inspected no less frequently than every hour, and changed when obstruction is a concern, or once every 24 hours.

Devices that actively humidify inspired gas are not recommended. They cause problems with ventilation and monitoring since anesthesia machines are not designed to handle large amounts of condensed water within their breathing circuit.

Unique safety issues

- The need to place a second high-quality viral filter (typically a pleated mechanical filter that does not need heat and humidity exchange properties) on the expiratory limb of an anesthesia machine breathing circuit used for ventilation of a COVID-19 patient, even if a filter or HMEF is placed at the airway (figure 1) (see "Coronavirus disease 2019 (COVID-19): Anesthetic concerns, including airway management and infection control", section on 'Contamination of the internal components of the anesthesia machine'). The filter at the expiratory limb can likely be left in place for a longer period of time than the filter placed at the airway; however, there are no data predicting filter performance over time. Since many institutions have filter shortages, these expiratory limb filters should only be changed as necessary.

- Potential need to prevent accidental administration of inhalation anesthetic agents. If there are no plans to administer inhalation anesthetics to achieve patient sedation, then the vaporizers for the volatile agents should be removed or drained. Also, the nitrous oxide (N_2O) cylinder and pipeline hoses should be removed. These measures ensure that inhalation anesthetic agents are not accidentally administered.

  However, some institutions with inadequate supplies of the intravenous sedatives and analgesic agents that are commonly used in the ICU may consider emergency use of low doses of a volatile inhalation anesthetic agent (isoflurane or sevoflurane), as explained below. (See 'Use of inhalation anesthetics for sedation' below.)

- The potential for the CO_2 absorbent to expire. The inspired CO_2 and the color indicator of the CO_2 absorbent should be monitored frequently. The absorbent should be replaced if inspired CO_2 increases (eg, above 5 mmHg) or if the CO_2 absorbent color indicates that it has become exhausted. If ventilation must be interrupted to change the absorbent, the patient should be temporarily ventilated by an alternative means. Furthermore, potential reactions with the CO_2 absorbent may occur if a volatile anesthetic agent is employed and the absorbent becomes

dried by the FGF. (See "Anesthesia machines: Prevention, diagnosis, and management of malfunctions", section on 'Carbon dioxide absorbent exhaustion or toxicity'.)

There are three reasons not to simply remove the CO_2 absorber canister, or use an empty absorber canister:

- CO_2 absorption is important to prevent hypercarbia if FGF decreases below 1 to 1.5 times minute ventilation (purposely or inadvertently).
- The breathing system may leak if the canister is removed. The valve installed on some machines to prevent a leak is intended for use for short periods while the canister is being changed, and is not dependable for longer-term use
- The canister should not be left empty because that would significantly increase the compliance of the breathing system.

- Potential need to adjust the scavenger system of the anesthesia machine. If an anesthesia machine is used outside of an OR, it may not be possible to connect its scavenger system to a compatible waste anesthesia gas disposal or vacuum outlet. Waste anesthetic gas disposal outlets are typically only found in operating or procedure rooms, and waste gas hoses from the anesthesia machine may not be compatible with medical vacuum outlets found elsewhere. Waste anesthetic gas scavenging is only necessary when use of inhalation anesthetic agents is planned (see 'Use of inhalation anesthetics for sedation' below). Importantly, if a scavenger system with a reservoir bag (closed scavenger system) is not connected to vacuum, it can cause high PEEP and peak pressures due to backup of waste gas into the breathing system. Options include:
  - If no inhalation anesthetic agents are to be used (picture 1):
    - Disconnection of the scavenger system from the hoses coming from the breathing system and ventilator
    - Removal of the scavenger reservoir bag (if it is a closed scavenger system)
  - If inhalation anesthetic agent will be used, scavenging is required. Connection of the scavenger system to suction in locations outside the OR (eg, the ICU) may be difficult if the connections are incompatible. In such cases, alternate tubing or connectors, or connection adapters may be used. When higher than usual FGFs are used, scavenger suction must be adjusted upward to ensure proper function.
- Potential need to modify oxygen utilization by the anesthesia machine ventilator if institutional oxygen supply is limited by factors such as [3,9]:

- Delay in delivery of liquid oxygen to the hospital
- Excessive use of oxygen by the hospital, such that the oxygen vaporizers (where liquid oxygen is converted to gas oxygen) become covered in ice, resulting in inefficiency
- Inability of the flow in an oxygen pipeline branch to keep up with demand due to caliber of the pipeline, and the number of ventilators, anesthesia machines, and oxygen flowmeters on that branch. This is more typically a problem in some older hospitals.

When the oxygen consumption outstrips the maximum oxygen supply, all the ventilators, anesthesia machines, and oxygen flowmeters on that pipeline branch will be affected. Thus, the inspired oxygen concentration delivered by an individual anesthesia machine will decrease if air is being used, and the machine alarm may activate during each inspiratory cycle.

Anesthesia machines with bellows ventilators typically use oxygen as the drive gas that compresses the bellows; these ventilators consume oxygen at a rate approximating minute ventilation plus additional oxygen used in the FGF at the rate of FGF times percent oxygen, with sporadic consumption that increases dramatically during inspiration. However, machines with bellows ventilators may be modified by a qualified clinical engineer to be powered by compressed air instead of oxygen [3,9], a modification made that must be made when the machine is not in use (refer to the APSF/ASA Guidance on Purposing Anesthesia Machines as ICU Ventilators).

Conversely, anesthesia machines with electrically powered (ie, piston or turbine) ventilators are similar to ICU ventilators, in that they typically consume oxygen at the rate of minute ventilation times percent oxygen, and do not consume oxygen above what is delivered in the fresh gas.

- The need for periodic performance of an anesthesia machine self-test (ie, power-up test) approximately every 24 to 72 hours. The ASA and anesthesia machine manufacturers recommend a pre-use check every day prior to using the machine in the OR setting. For prolonged use, most manufactures have stated that this can be done approximately every three days. Experience has shown that problems such as inaccurate ventilation delivery and monitoring may occur when anesthesia machines are not restarted and checked at three-day intervals.

  Notably, an alternative means of ventilation is necessary (eg, with a manual resuscitator or a second ventilator) while the machine is powered down, restarted, and checked. A step-by-step procedure should be followed to ensure that all equipment is available to prevent patient lung de-recruitment, as well as to limit spillage of breathing circuit gas and other contaminants and protect anesthesia personnel during this process (refer to APSF/ASA Guidance on Purposing

Anesthesia Machines as ICU Ventilators and the ASA's Quick Reference: Setup and Monitoring Instructions – Anesthesia Machines as an ICU Ventilator) [4,5]. A suggested procedure has been developed by the APSF and ASA (refer to the APSF/ASA Procedure for Supporting Patients during the Anesthesia Machine Self-Test) [10].

- The need to periodically check the breathing circuit for possible kinking or compression since, unlike ICU ventilators, there is no articulating arm on the anesthesia machine that can hold the breathing circuit up off the bed.

- The need to minimize potential for errors in setup of anesthesia machines, initiation of controlled ventilation, and respiratory monitoring in locations outside of the OR suite, ideally by deploying multiple machines of the same model within any one hospital unit (eg, ICU, post-anesthesia care unit [PACU]).

Adjusting ventilatory settings

- The need to understand how specific capabilities differ among individual anesthesia machines:

  - Newer anesthesia machines have ventilator capabilities similar to modern ICU ventilators, with more flexible settings that can deliver more modes of ventilation (including assist modes) compared with older models. Newer models with compliance compensation and tidal volume delivery unaffected by changes in FGF are generally preferred (refer to the APSF/ASA Guidance on Purposing Anesthesia Machines as ICU Ventilators).

  - Newer machines are also equipped with breathing systems and ventilators that can be sterilized between patients, and are better choices for those with COVID-19 infection.

  - Older models can be reserved for surgical patients and for ventilation of patients without COVID-19 respiratory disease, if feasible.

- The need to understand how settings and performance of anesthesia machine ventilators differ from those of ICU ventilators when making adjustments in ventilator settings:

  - Anesthesia machines do not default to pressure support of extra breaths in control modes. Care must be taken to add this when changing ventilator modes.

  - Anesthesia machines may have a lower peak inspiratory flow rate. Negative airway pressure occurs if the patient inhales faster than the maximum inspiratory flow rate provided by the ventilator.

  - Anesthesia machines are milliseconds slower to respond to patient effort because of the circle breathing system interposed between the patient and anesthesia ventilator [11],

which can cause more hyperventilation in an air-hungry patient.

- Inspiratory time is not directly set on an anesthesia machine. Most anesthesia machines do not provide direct control of inspiratory time; instead this is controlled indirectly by setting the I:E ratio and the respiratory rate.

  Options for setting the anesthesia machine ventilator include:

  - In volume control modes (including synchronized intermittent mandatory ventilation [SIMV]), the inspiratory flow rate can be increased by increasing tidal volume or by decreasing inspiratory time (accomplished by reducing the I:E ratio or by increasing the respiratory rate). Introducing an inspiratory pause (Tpause or T_{IP}) will also increase the inspiratory flow rate during the active portion of inspiration, before the pause.

  - In pressure control or support modes, the inspiratory flow rate can be increased by lowering the flow trigger level for ventilation (which also increases the speed at which pressure-support is provided), or by decreasing the rise time of pressure support (which increases the inspiratory flow rate). On Draeger anesthesia machine ventilators, the flow trigger level is called "Trigger L/min" and the rise time is called "Tslope." On GE Healthcare Systems anesthesia machine ventilators, the flow trigger level is called "Flow Trigger" and the rise time is called "Rise Rate." However, lowering the flow trigger level may cause extra mis-triggered breaths in some patients; if these occur, the flow trigger level must be increased. On some Draeger machine ventilators, the maximum inspiratory flow is governed by a facility-level setting, although on-site clinical engineers can adjust this parameter to allow a maximum inspiratory flow of 75 L/min.

- Potential need to modify default ventilator parameters and alarm settings. Default settings on the anesthesia machine, such as minute ventilation, airway pressure, positive end-expiratory pressure (PEEP) levels, and alarms, may be modified to better match those of an ICU ventilator. The default alarm volumes should be set to maximum.

- The potential for the fraction of inspired oxygen (FiO_2) concentration in the breathing circuit to be lower than the set oxygen gas concentration on the anesthesia machine (FgO_2), especially at lower FGFs. Because of the rebreathing that occurs in an anesthesia machine circle breathing circuit, inspired oxygen concentration depends on both the ratio of oxygen to air in the delivered fresh gas (determined by the FGF setting) and the total FGF (which influences the amount of rebreathing). Thus, inspired oxygen concentration must be continuously monitored (see 'Monitoring during sedation with inhalation anesthetics' below).

- Notably, when total FGF is very high (eg, >12 L/minute), a FiO2 of 100 percent cannot be delivered if the total FGF is higher than the maximum possible flow of oxygen. For instance, if a total FGF of 15 L/minute is necessary, and the maximum oxygen flow is only 12 L/min, then 3 L/min of air must be added. This may be confusing on anesthesia machines that have controls for total FGF and for oxygen percent.

Monitoring long-term ventilation — An anesthesia professional should be available to start ventilation and subsequently monitor degree of moisture accumulation, inspired and expired CO_2, filter integrity, overall anesthesia machine function, and effectiveness of ventilation [1]. (See "Coronavirus disease 2019 (COVID-19): Critical care and airway management issues", section on 'Ventilator management of acute respiratory distress syndrome'.)

The APSF/ASA guidelines address additional maintenance and monitoring requirements during use of anesthesia machines for long-term ventilation of COVID-19 patients (refer to APSF/ASA Guidance on Purposing Anesthesia Machines as ICU Ventilators and Quick Reference: Setup and Monitoring Instructions - Anesthesia Machine as an ICU Ventilator) [4,5]. These additional considerations are necessary due to use of extra filters which may become clogged, the tendency to accumulate condensed water in the breathing circuit, and risks for aerosolizing droplets containing COVID-19 virus.

Documentation of this enhanced monitoring of continuous and intermittent parameters is necessary. This may be achieved automatically if the anesthesia machine connected to the hospital network for recording to the electronic medical record [1], or manually using a template developed for this purpose by the anesthesia team.

Patient monitoring — Baseline monitored parameters (eg, tidal volume, plateau pressure [Pplat], minute ventilation) should be recorded when ventilation is initiated. If spirometry is available, saving or photographing the baseline tracings and reference loops may aid in later diagnosis of filter obstructions.

Continuously monitored parameters (with preset alarms) that are checked and recorded each hour include:

- Inspired oxygen concentration.
- Inspired and expired CO_2.
- Inspiratory pressure.
- Tidal volume and respiratory rate.

- Low oxygen pressure alarm. If an anesthesia machines with an oxygen-driven bellows is being used, a low oxygen pressure alarm triggered by each inspiration may indicate a high demand on the institutional central oxygen pipeline system, particularly when multiple ventilators are simultaneously in use. (See 'Differences between anesthesia machine ventilators and ICU ventilators' above.)

Intermittently monitored ventilatory and physiologic parameters include:

- Check Pplat at least once **every four hours**, and after each change in PEEP or tidal volume, to ensure that it is ≤30 cm H_2O. Measurement of Pplat is accomplished during a 0.5 second inspiratory pause. Unlike many ICU ventilators, anesthesia machines do not have a control to manually initiate an inspiratory pause. On an anesthesia machine ventilator, a 0.5 second inspiratory pause can be generated by temporarily setting the mode to volume ventilation with the tidal volume that the patient has been receiving, at 10 breaths per minute, with an I:E ratio of 1:2 and a 50 percent inspiratory pause (Tpause or T_{IP}). (See 'Adjusting ventilatory settings' above.)

- Check the flow readings approximately **every four hours**, since these may become less accurate over time. If the machine is equipped with both inspiratory and expiratory flow sensors, a gradual increase in the difference between inspired and exhaled tidal volume measurements usually indicates that a startup test is needed to recalibrate the breathing system flow sensors.

- Confirm there is no leak around the endotracheal tube cuff **every hour** because such a leak produces respiratory droplets and aerosolized viral particles. A leak around the endotracheal tube cuff typically manifests as measured exhaled tidal volume that is lower than measured inhaled tidal volume, and a flow-volume loop that does not close [12]. At low FGFs a bellows ventilator may progressively empty, while the reservoir bag will progressively deflate in machines with a piston or turbine ventilator. High FGF compensates for small leaks, obscuring these indicators of breathing circuit volume.

Machine maintenance and monitoring — Intermittent inspection and maintenance of proper anesthesia machine and breathing circuit function including:

- Inspect the breathing circuit hoses and water trap for excessive condensed water **every hour**. An oscillating obstructive gas flow tracing during exhalation indicates condensed water accumulation in the expiratory, scavenger, or ventilator hose. An oscillating obstructive gas flow tracing during inhalation indicates condensed water accumulation in the inspiratory or ventilator hose.

If fluid has accumulated in the breathing circuit and is threatening to impede ventilation, it must be removed [3]. Plans should be in place to ventilate the patient while the circuit is emptied. One novel method that has been described is placement of an airway filter casing with a Luer connector in the expiratory limb to serve as a water trap, enabling aspiration of condensed water by syringe without interrupting ventilation [3]. Further, proper collection and disposal procedures for contaminated water and PPE for personnel performing this procedure are necessary since the fluid being removed may be contaminated with virus.

- Inspect the breathing circuit hoses for possible kinking or compression **every hour** as well.

- Inspect the airway and expiratory limb breathing circuit filters **every hour** to check for excessive humidity or secretions that may cause obstruction of gas flow. The airway filter is at highest risk (figure 1). Obstructed filters must be changed. Otherwise, filters are typically replaced every 24 hours.

  High peak airway pressure during volume ventilation or low tidal volume during pressure ventilation are signs of profound obstruction of the filters placed at the airway or in the expiratory limb (figure 1) [3]. Decreased peak expiratory flow and prolongation of expiratory flow are earlier indications of partial obstruction of one of these filters [12]. Significant obstruction of either filter also creates additional PEEP, with a difference between the set and actual PEEP that can be seen in the airway pressure when the expiratory limb filter is obstructed. Notably, this additional PEEP is invisible when the airway filter is obstructed since airway pressure is measured downstream of that filter.

- Check the CO_2 absorbent color and inspired CO_2 values **every hour** to ensure that the absorbent is still functioning properly and does not need to be exchanged. This is especially important if lower FGFs are being used.

- Confirm that an anesthesia machine startup test was performed once **every 24 to 72 hours** (refer to the APSF/ASA Procedure for Supporting Patients during the Anesthesia Machine Self-Test) [10]. (See 'Differences between anesthesia machine ventilators and ICU ventilators' above.)

USE OF INHALATION ANESTHETICS FOR SEDATION

During the COVID-19 pandemic, shortages of the intravenous sedatives and analgesic agents that are usually employed to sedate critically ill patients during mechanical ventilation may lead some institutions to consider using low doses of a potent volatile inhalation anesthetic agent (isoflurane or sevoflurane) [13]. Compared with other critically ill patients requiring mechanical ventilation, patients

with acute respiratory distress syndrome (ARDS) due to COVID-19 have higher sedation requirements that may be due to their younger age, higher respiratory drive, and a particularly intense inflammatory response [14,15]. Although we are not recommending routine administration of inhalation anesthetic agents to critically ill patients for prolonged periods due to scant safety data in this setting, as well as some disadvantages (see 'Advantages and disadvantages' below), the ready availability of these agents is an advantage when anesthesia machines are used to provide mechanical ventilation. (See "Coronavirus disease 2019 (COVID-19): Critical care and airway management issues", section on 'Sedation and analgesia'.)

The American Society of Anesthesiologists (ASA) and the Anesthesia Patient Safety Foundation (APSF) have developed guidelines for such emergency use (refer to the APSF/ASA Guidance for Use of Volatile Anesthetic for Sedation of ICU Patients) [16].

Intravenous sedative-analgesic regimens that are usually employed to sedate critically ill patients during mechanical ventilation are discussed in separate topics:

- (See "Sedative-analgesic medications in critically ill adults: Selection, initiation, maintenance, and withdrawal".)
- (See "Sedative-analgesic medications in critically ill adults: Properties, dosage regimens, and adverse effects".)
- (See "Pain control in the critically ill adult patient".)

Dosing to achieve sedation — Administration of low doses of either sevoflurane (eg, 0.5 to 1.4 percent) or isoflurane (eg, 0.2 to 0.7 percent) for long-term sedation is reasonable if use of a volatile inhalation anesthetic agent becomes necessary.

Factors influencing dosing include whether the targeted level of sedation is achieved with satisfactory patient comfort. The presence of ventilator dyssynchrony may necessitate deepening the anesthetic/sedation level. Conversely, if hypotension is present, lightening of the anesthetic/sedation level is necessary. (See "Inhalation anesthetic agents: Clinical effects and uses", section on 'Clinical effects'.)

When the decision is made to allow the patient to awaken, the anesthetic vaporizer is turned off, and fresh gas flow (FGF) is increased. Washout of anesthetic agent is rapid and predictable, with patients typically able to respond to commands and be assessed for extubation within 10 to 15 minutes. (See "Emergence from general anesthesia", section on 'Inhalation agents'.)

Monitoring during sedation with inhalation anesthetics — In addition to the suggested monitoring noted above for use of anesthesia machines for long-term ventilation (see 'Monitoring

long-term ventilation' above), specialized monitoring requiring the constant presence of an anesthesia provider is necessary during administration of inhalation anesthetic agents.

Patient monitoring during sedation

- Continuously monitored parameters include:
  - End-tidal anesthetic concentration, with titration of anesthetic dosing to the minimal effective end-tidal concentration. The low-level and high-level alarms on the anesthetic gas monitor should be enabled.
  - Exhaled end-tidal carbon dioxide ($ETCO_2$) to monitor for the possibility of malignant hyperthermia (which severely and acutely increases $ETCO_2$), and to help manage ventilation. (See 'Monitoring long-term ventilation' above.)
  - Temperature, since potent inhalation anesthetics lower core temperatures (see "Perioperative temperature management", section on 'Anesthetic effects on thermoregulation'), and to monitor for the possibility of malignant hyperthermia (which acutely increases temperature to >102°F [38.9°C).
- Other monitored parameters include:
  - Hemodynamic monitoring per usual standards for care of individual critically ill patients, and may be useful to evaluate cardiovascular responses to an inhalation anesthetic agent. (See "Acute respiratory distress syndrome: Supportive care and oxygenation in adults", section on 'Hemodynamic monitoring' and "Inhalation anesthetic agents: Clinical effects and uses", section on 'Cardiovascular effects'.)
  - Serum creatinine and liver function tests are obtained at intervals that may be daily (in consultation with the critical care team), as a check for renal or hepatic dysfunction during long-term administration of a volatile anesthetic agent.

Equipment monitoring during sedation — Intermittent inspection and maintenance of anesthetic administration includes:

- The fill level of anesthetic vaporizers is checked **every hour** since rapid utilization of volatile inhalation anesthetic agents occurs due to high FGF; refill when anesthetic level <20 percent full.

  Liquid anesthetic use can be estimated. One mL of a liquid volatile anesthetic agent yields approximately 200 mL of gas anesthetic (specific values are 195 mL for isoflurane or 184 mL for sevoflurane). Thus, at 10 L/min of FGF, the liquid volatile anesthetic consumption is

approximately 30 mL/hour if a 1 percent inhaled concentration is delivered. Most vaporizers hold approximately 200 ml of liquid, so refills would be needed multiple times each day even at the lower doses noted above for use of isoflurane or sevoflurane for patient sedation during mechanical ventilation. (See 'Dosing to achieve sedation' above.)

One way to reduce consumption of volatile anesthetic agent is to reduce FGF. Another way to agent consumption is to use an anesthetic reflector device such as the AnaConDa or Mirus [17-22]. These devices are designed for administration of inhalation anesthetic agents using a traditional intensive care unit (ICU) ventilator, but are not approved for use in the United States. The device is placed between the Y-piece and patient, where it vaporizes small amounts of anesthetic liquid, and absorbs most of the exhaled anesthetic, which is then re-inhaled on the next breath (much like a heat and moisture exchanger [HME] absorbs and conserves humidity). Notably, room contamination still occurs with use of these devices unless a scavenging system is employed [20-22].

- Proper functioning of the scavenging system is confirmed when administration of inhalation anesthetics is initiated, then **every 24 hours** or after major changes in the rate of FGF. Anesthetic vapor is consumed rapidly and the scavenger system requires high vacuum flow when high FGF is used.

Advantages and disadvantages — Advantages and disadvantages of specific agents (sevoflurane versus isoflurane) are discussed separately. (See "Inhalation anesthetic agents: Clinical effects and uses", section on 'Sevoflurane' and "Inhalation anesthetic agents: Clinical effects and uses", section on 'Isoflurane'.)

Potential advantages and disadvantages for long-term use of sevoflurane or isoflurane for sedation of mechanically ventilated patients with COVID-19 induced respiratory failure include:

- **Advantages**
  - Effective sedative effects, with rapid onset and offset allowing easy titratability. (See "Inhalation anesthetic agents: Clinical effects and uses", section on 'Sedation and anesthesia'.)
  - Minimal metabolism and likely minimal organ toxicity. (See "Inhalation anesthetic agents: Properties and delivery", section on 'Metabolism'.)
  - Ready availability during shortages of the intravenous sedatives and analgesic agents that are usually employed for sedation during mechanical ventilation [13]. Reports of unusually high sedation requirements in many COVID-19 patients may contribute to shortages of multiple commonly used intravenous agents [13,14]. (See "Coronavirus disease 2019

(COVID-19): Critical care and airway management issues", section on 'Sedation and analgesia'.).

- Potentially advantageous respiratory effects
  - Bronchodilation, with attenuation of bronchospasm and decreased airway responsiveness. (See "Inhalation anesthetic agents: Clinical effects and uses", section on 'Respiratory effects'.)
  - Pulmonary anti-inflammatory effects (eg, reduction of pro-inflammatory cytokine release) that may minimize the extent of lung injury [23-27]. (See "One lung ventilation: General principles", section on 'Intravenous versus inhalation anesthetics'.)
- Dose-dependent muscle relaxation during mechanical ventilation. (See "Inhalation anesthetic agents: Clinical effects and uses", section on 'Skeletal and smooth muscle relaxation'.)

- **Disadvantages**
  - Scant safety data regarding use of inhalation anesthetic agents for prolonged periods in critically ill patients. However, long-term sedation with sevoflurane or isoflurane has been employed in some nations for sedation of patients with adult respiratory distress syndrome (ARDS) or other critical illness, without evidence of renal or hepatic injury [26-30].
  - Rapid utilization of volatile inhalation anesthetic agents occurs due to high FGF. Thus, hourly inspection of the anesthetic vaporizer fill level and analysis of end-tidal anesthetic concentration are particularly important. (See 'Monitoring during sedation with inhalation anesthetics' above.)
  - Potential for inadequate sedation due to a vaporizer running dry, particularly if the patient has received a neuromuscular blocking agent. Thus, the patient and anesthesia machine and anesthetic vaporizer must be carefully monitored.
  - Potential difficulty with connection of the anesthesia machine scavenger systems to compatible waste anesthesia gas disposal outlets in settings outside an operating room (OR). (See 'Differences between anesthesia machine ventilators and ICU ventilators' above.)
  - Lack of familiarity among non-anesthesia personnel caring for critically ill patients with ARDS (eg, intensivists, nurses, respiratory therapists) regarding use of anesthesia machines to administer volatile inhalation anesthetic agents, dosing of these agents, and

potential pitfalls that may occur during their administration (refer to the APSF/ASA Guidance for Use of Volatile Anesthetic for Sedation of ICU Patients) [16].

- Need for constant presence of anesthesia personnel as recommended by the ASA and APSF (refer to the APSF/ASA Guidance for Use of Volatile Anesthetic for Sedation of ICU Patients) [16].

- Potentially undesirable systemic effects of a potent volatile anesthetic agent in critically ill patients, including:

  - Cardiovascular effects (eg, myocardial depression and vasodilatory properties that result in dose-dependent reductions in blood pressure and cardiac output). (See "Inhalation anesthetic agents: Clinical effects and uses", section on 'Cardiovascular effects'.)

  - Adverse respiratory effects including airway irritation, particularly with the more pungent agents such as isoflurane, as well as respiratory depression. (See "Inhalation anesthetic agents: Clinical effects and uses", section on 'Respiratory effects'.)

  - Cerebral effects (eg, dose-dependent cerebral vasodilation, with blunting of cerebral autoregulation by uncoupling cerebral blood flow (CBF) and metabolism, thereby increasing CBF and intracranial pressure (ICP). Thus, patients with known or suspected elevations in ICP are not candidates for sedation with inhalation anesthetic agents. (See "Inhalation anesthetic agents: Clinical effects and uses", section on 'Effects on cerebral physiology'.)

- Although rare, potential for potent inhalation anesthetic agents to cause malignant hyperthermia. (See "Inhalation anesthetic agents: Clinical effects and uses", section on 'Malignant hyperthermia (volatile inhalation agents)'.)

COLLABORATION WITH CRITICAL CARE CONSULTANTS

Collaboration and coordination with critical care clinicians is essential for care of COVID-19 patients regarding the initial decision to use an anesthesia machine, and for management of long-term ventilation and comorbidities in each critically ill COVID-19 patient (eg, cardiovascular and renal complications, coinfection with sepsis) [31-35]. These issues are discussed in detail in separate topics:

- (See "Coronavirus disease 2019 (COVID-19): Critical care and airway management issues".)
- (See "Coronavirus disease 2019 (COVID-19): Myocardial injury".)

- (See "Coronavirus disease 2019 (COVID-19): Issues related to kidney disease and hypertension".)

SOCIETY GUIDELINE LINKS

Links to society and government-sponsored guidelines from selected countries and regions around the world are provided separately. (See "Society guideline links: Coronavirus disease 2019 (COVID-19) – International and government guidelines for general care" and "Society guideline links: Coronavirus disease 2019 (COVID-19) – Guidelines for specialty care" and "Society guideline links: Coronavirus disease 2019 (COVID-19) – Resources for patients".)

INFORMATION FOR PATIENTS

UpToDate offers two types of patient education materials, "The Basics" and "Beyond the Basics." The Basics patient education pieces are written in plain language, at the 5th to 6th grade reading level, and they answer the four or five key questions a patient might have about a given condition. These articles are best for patients who want a general overview and who prefer short, easy-to-read materials. Beyond the Basics patient education pieces are longer, more sophisticated, and more detailed. These articles are written at the 10th to 12th grade reading level and are best for patients who want in-depth information and are comfortable with some medical jargon.

Here are the patient education articles that are relevant to this topic. We encourage you to print or e-mail these topics to your patients. (You can also locate patient education articles on a variety of subjects by searching on "patient info" and the keyword(s) of interest.)

- Basics topics (see "Patient education: Coronavirus disease 2019 (COVID-19) overview (The Basics)")

SUMMARY AND RECOMMENDATIONS

- Contamination of an anesthesia machine, its breathing system and ventilator, and its connected gas analyzer is more likely during use as an intensive care ventilator compared with use during surgical procedures for patients with novel coronavirus disease 2019 (COVID-19 or nCoV) infection because of the duration and extent of machine exposure. However, if two filters are used (eg, a heat and moisture exchange filter [HMEF] containing an electrostatic filter placed at the airway plus a mechanical pleated filter placed at the expiratory limb of the breathing circuit), the combined viral filtration efficiency (VFE) is very high, rendering contamination of the

anesthesia machine unlikely, even when used for multiple days (with fresh filters each day). (See 'Prevention of anesthesia machine contamination' above.)

- Locations selected for use of anesthesia machines to ventilate COVID-19 patients will be institution-dependent depending on layout of selected hospital area(s), location of rooms with negative pressure capabilities, availability of sources of high-pressure oxygen and medical air, availability of compatible connections from the scavenger system to waste anesthesia gas disposal outlets when inhalation anesthetic agents are used, and availability of anesthesia personnel to manage the anesthesia machines. (See 'Locations for anesthesia machines' above.)

- The American Society of Anesthesiologists (ASA) and the Anesthesia Patient Safety Foundation (APSF) have developed guidance for repurposing of anesthesia machines for longer-term ventilation (refer to the APSF/ASA Guidance on Purposing Anesthesia Machines as ICU Ventilators and Quick Reference: Setup and Monitoring Instructions – Anesthesia Machine as an ICU Ventilator). Although newer anesthesia ventilators incorporate multiple controlled and assisted modes of ventilation that are nearly identical to ventilators in the intensive care unit (ICU), several important technical issues are unique to anesthesia machines during such use (see 'Differences between anesthesia machine ventilators and ICU ventilators' above):

    - The age and specific capabilities of individual anesthesia machines (newer anesthesia machines have more flexible capabilities and can deliver more modes of ventilation).

    - The need to adjust fresh gas flow (FGF) to prevent condensed water accumulation in the breathing circuit.

    - The need for long-term humification and warming of inspired gases.

    - The need for two high-quality viral filters (one at the airway and on the expiratory limb of the breathing circuit (figure 1)).

    - The need to understand how settings and performance of anesthesia machine ventilators can be different from those of ICU ventilators.

    - Potential need to modify default ventilator parameters and alarm settings.

    - The potential for the carbon dioxide (CO_2) absorbent to expire.

    - The potential for the fraction of inspired oxygen (FiO_2) concentration in the breathing circuit to be lower than the set oxygen gas concentration on the anesthesia machine (FgO_2).

- The need to prevent accidental administration of inhalation anesthetic agents, if inhalation anesthetics are not administered to achieve patient sedation.
- Potential need to adjust the scavenger system to prevent backpressure in the breathing system if the anesthesia machine is used outside of an operating room (OR).
- The need for periodic performance of an anesthesia machine self-test (ie, power-up test) approximately every 24 to 72 hours.
- The need to periodically check the breathing circuit for possible kinking or compression.
- The need to minimize potential for errors in setup of anesthesia machines, initiation of controlled ventilation, and respiratory monitoring in locations outside the OR, ideally by deploying multiple machines of the same model within any one hospital unit.

- An anesthesia professional should be available to start and monitor ventilation and overall anesthesia machine function (see 'Monitoring long-term ventilation' above):
  - Continuously or intermittently monitored patient parameters (with preset alarms) that are checked and recorded each hour include (see 'Patient monitoring' above):
    - Inspired oxygen concentration
    - Inspired and expired CO_2
    - Inspiratory pressure
    - Tidal volume and respiratory rate
    - Low oxygen pressure alarm
    - Check Pplat at least once **every four hours**, and after each change in positive end-expiratory pressure (PEEP) or tidal volume
    - Check the flow readings approximately **every four hours**
    - Confirm there is no leak around the endotracheal tube cuff **every hour**
  - Intermittently machine monitoring includes inspection of (see 'Machine maintenance and monitoring' above):
    - Breathing circuit hoses and water trap for excessive condensed water **every hour**.
    - Breathing circuit hoses for possible kinking or compression **every hour**
    - Airway and expiratory limb breathing circuit filters **every hour** for excessive humidity or secretions
    - CO_2 absorbent color and inspired CO_2 values **every hour**
    - Documentation of anesthesia machine startup test performance once **every 24 to 72 hours**

- Although intravenous sedative-analgesic regimens are usually employed to sedate critically ill patients during mechanical ventilation, institutions with shortages of these intravenous agents may consider using low doses of a potent volatile inhalation anesthetic agent for long-term sedation (ie, sevoflurane [0.5 to 1.4%] or isoflurane [0.2 to 0.7%]; refer to the APSF/ASA Guidance for Use of Volatile Anesthetic for Sedation of ICU Patients). (See 'Use of inhalation anesthetics for sedation' above and 'Dosing to achieve sedation' above.)

- Advantages and disadvantages of use of inhalation anesthetic agents in this setting include (see 'Advantages and disadvantages' above):

  - Advantages

    - Effective sedative effects, with rapid onset and offset allowing easy titratability
    - Minimal metabolism and likely minimal organ toxicity
    - Readily available
    - Advantageous respiratory effects including bronchodilation and possible pulmonary anti-inflammatory effects
    - Dose-dependent muscle relaxation

  - Disadvantages

    - Scant safety data regarding use of inhalation anesthetic agents for prolonged periods
    - Lack of familiarity among non-anesthesia personnel caring for critically ill patients
    - Need for constant presence of anesthesia personnel
    - Rapid utilization of volatile inhalation anesthetic agents due to high FGF, with the potential for inadequate sedation
    - Potential difficulty with connection of the anesthesia machine scavenger systems to compatible waste anesthesia gas disposal outlets
    - Potentially undesirable cardiovascular, respiratory, or cerebral effects of potent volatile anesthetic agents in critically ill patients
    - Although rare, potential for malignant hyperthermia

- Specialized additional monitoring is necessary if inhalation anesthetics are administered for long-term sedation, requiring the constant presence of an anesthesia provider and specialized monitoring that includes (see 'Monitoring during sedation with inhalation anesthetics' above):

  - Patient parameters (see 'Patient monitoring during sedation' above):

    - End-tidal anesthetic concentration, with low and high alarms
    - Exhaled end-tidal carbon dioxide ($ETCO_2$)

- Temperature
- Hemodynamic monitoring per usual standards for an individual critically ill patient
- Serum creatinine and liver function tests at appropriate intervals

- Equipment monitoring (see 'Equipment monitoring during sedation' above):

  - The fill level of anesthetic vaporizers is checked **every hour**
  - Proper functioning of the scavenging system is confirmed initially, then **every 24 hours** or after major changes in FGF rate

- Collaboration and coordination with critical care clinicians is essential regarding the initial decision for long-term ventilation with an anesthesia ventilator, and for management of ventilation and comorbidities in each critically ill patient (eg, cardiovascular and renal complications, coinfection with sepsis). (See 'Collaboration with critical care consultants' above.)

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