The Anesthesia Patient Safety Foundation Anesthesia Machine Workbook

http://www.anest.ufl.edu/vam

FREE WORKBOOK – NOT FOR SALE

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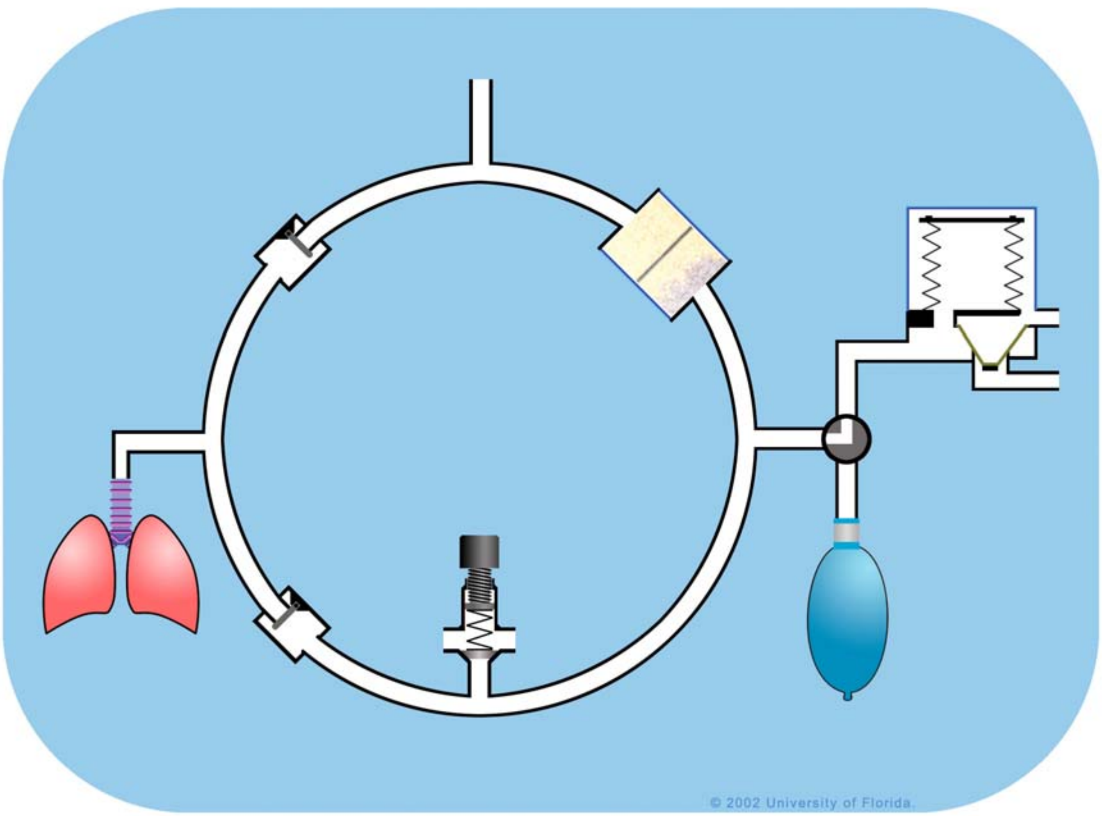

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Anesthesia Patient Safety Foundation (APSF) Anesthesia Machine Workbook

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Chapter 1
Normal function of traditional anesthesia machines (v 1.0)
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Introduction

This first chapter of the APSF anesthesia machine workbook consists of self-paced structured exercises that lead users through specific learning objectives related to normal function of traditional anesthesia machines such as those in the Modulus and Narkomed product lines. The workbook material is targeted mainly at US anesthesia providers but may also be generally applicable to traditional anesthesia machines used outside the United States. While newer anesthesia workstation designs are beginning to replace machines of traditional design, it is anticipated that the latter will continue to represent a significant share of the US fleet of anesthesia machines and therefore this presentation will not be obsolete for a few years to come.

Existing Virtual Anesthesia Machine (VAM) simulations at http://www.anest.ufl.edu/vam are used to support the learning objectives. Users are guided through a series of mouse click sequences with comments.

The learning objectives in this first chapter cover normal operation of a traditional anesthesia machine organized into different categories related to the different sections and functions of the anesthesia machine. Traditional ventilation modes are discussed. We propose to cover, in the future, new anesthesia workstation designs and ventilation modes like Pressure Controlled Ventilation (PCV), Pressure Support Ventilation (PSV) and Synchronized Intermittent Mandatory Ventilation (SIMV) in separate chapters that will form part of an electronic textbook that, as a living document, will grow in increments and will be revised as necessary.

Chapter 1: Normal function of traditional anesthesia machines
Chapter 2. FDA pre-use check of traditional anesthesia machines
Chapter 3: Failure modes of traditional anesthesia machines
Chapter 4. Normal function of new anesthesia workstation designs
Chapter 5. Pressure Control Ventilation – when and how to use
Chapter 6. Pressure Support Ventilation – when and how to use
Chapter 7. SIMV ventilation – when and how to use
Chapter 8 Failure modes of new anesthesia workstation designs

APSF anesthesia machine workbook – Chapter 1

Part 1. Basic concepts related to the anesthesia machine

Part 2. How the Virtual Anesthesia Machine (VAM) simulation works

Part 3. Specific safety-related exercises using VAM

Part 1. Basic concepts related to the anesthesia machine

In this section, we experiment with a different approach at developing basic concepts underlying anesthesia machine function. We invite the readers to join us in putting together an anesthesia machine from the ground up.

Basic Concepts:

What is the mission?

a: get gases out of the central supply and cylinders
b: meter them and load them with vapors
c: present them to the patient for breathing

What are the generic problems?

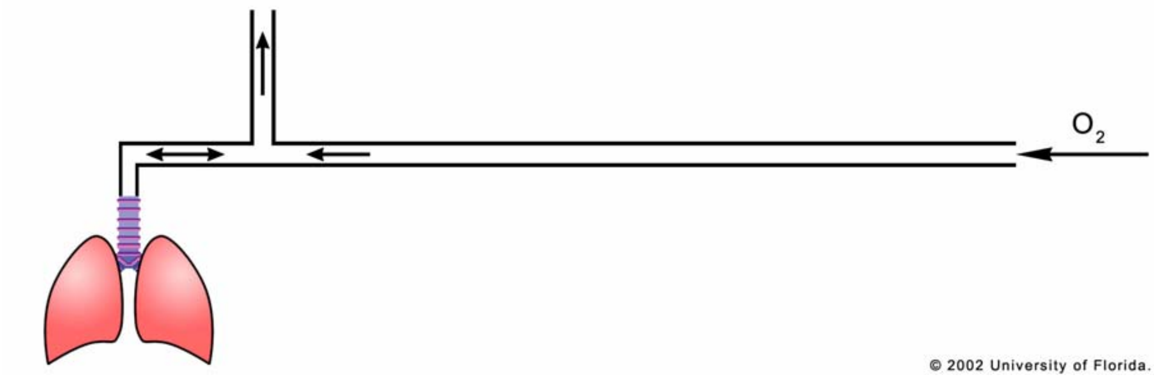
1. Establish and maintain an artificial atmosphere for the patient
2. Minimize anesthetic vapor consumption
3. Prevent unintended rebreathing
4. Breathe for the patient
5. Provide an exit route for gases

What are the dangers?
To exclude the patient from ambient air introduces a host of dangers that has cost many lives, particularly in patients who cannot breathe for themselves.

What are the special issues?
If patients cannot breathe by themselves, they become utterly dependent on manual or mechanical ventilation of their lungs, which engenders a multitude of problems.

Construct a system that:

1: Enables you to control the composition of the gases breathed by the patient.
  a: compressed gases
  b: vapors
2: Enables the patient to breathe spontaneously
3: Enables you to ventilate a paralyzed patient by pushing gas into the patient's lungs
  a: manually
  b: mechanically
4: Collects excess gas for disposal.



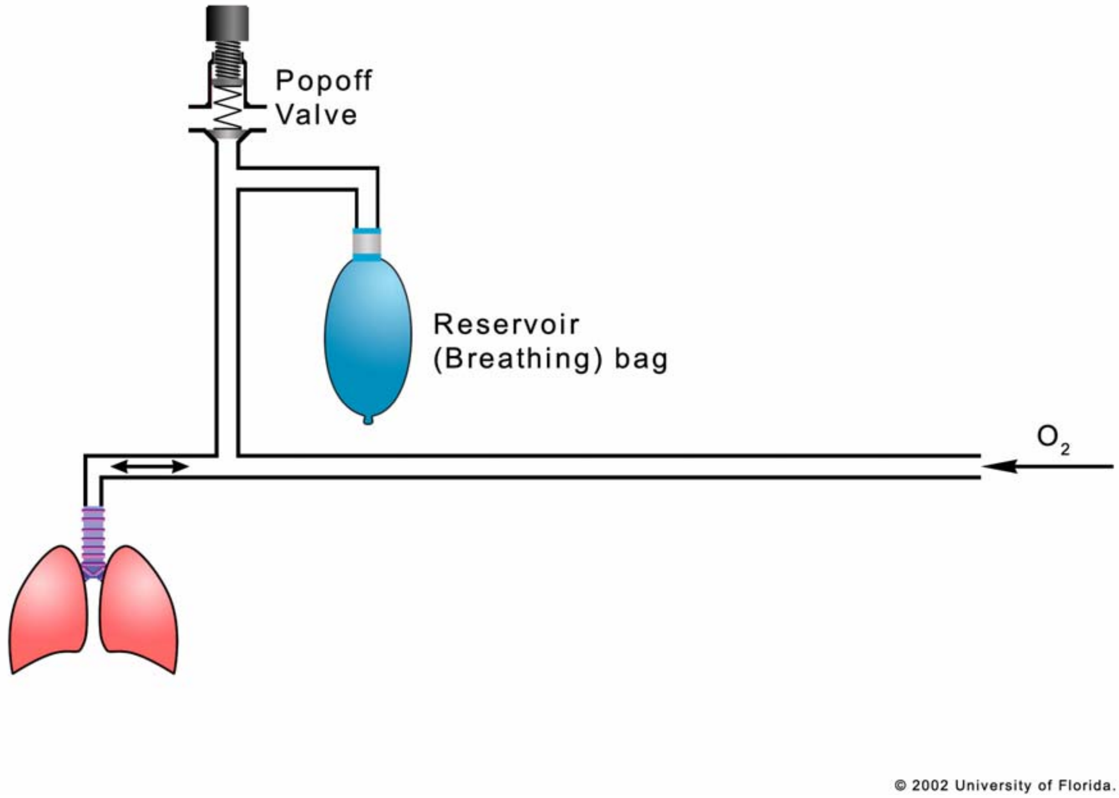
We start with ventilation using the simplest of systems.

Spontaneous ventilation
A source of oxygen supplies a continuous fresh gas flow (FGF). Because of the continuously flowing oxygen, the patient can exhale only through the outlet tube (upward pointing tube). During exhalation, the continuously flowing FGF is vented along with the patient's exhaled gas through the outlet tube. To prevent the patient from inhaling ambient air via the outlet tube, fresh gas flow must match the patient's inspiratory flow as it varies over time. To be on the safe side, a constant O_2 flow would have to match the peak inspiratory flow rate.

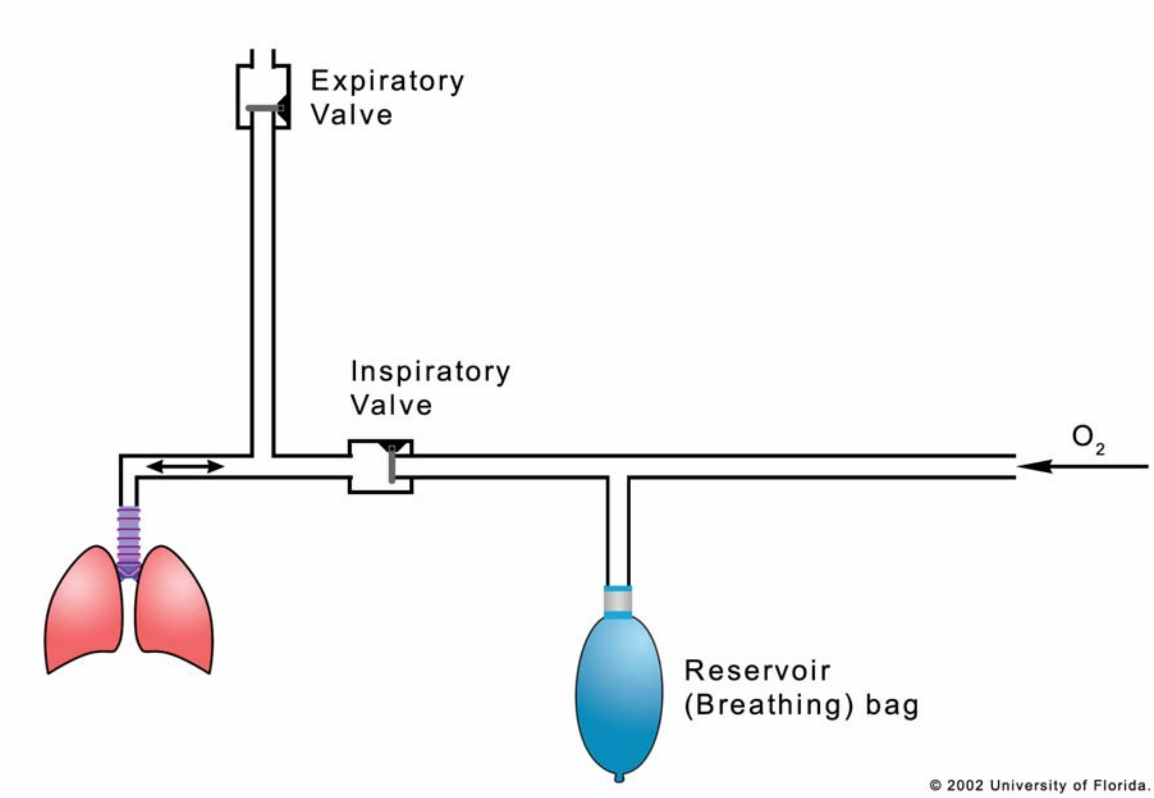
For the sake of simplicity, we are going to refer here only to tidal volume and minute ventilation, ignoring the fact that respiratory flow rates vary during the respiratory cycle. That is, we are going to assume that the patient's inspiratory flow is a constant, "square" waveform, instead of a sinusoid.

If the patient were to breathe only the supplied oxygen and if he were to spend ½ of each minute in inspiration (and obviously ½ in expiration), the fresh gas flow would have to be at least twice the patient's minute ventilation. Were he to spend only 1/3 of each minute in inspiration, we would have to supply his minute ventilation in 20 seconds, that is we would need to run at least 18 L/min for a patient with a minute ventilation of 6 L.

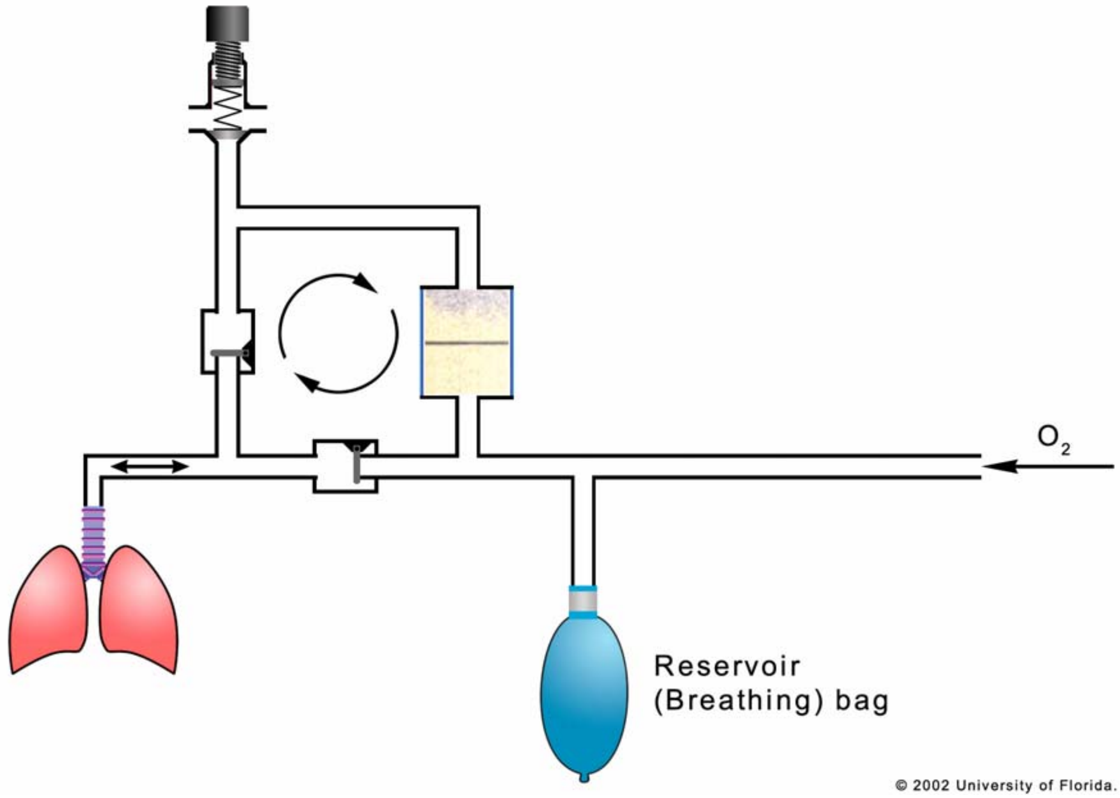
Positive pressure ventilation
By manually occluding the outlet port, for example, with a thumb, the continuous FGF is diverted into the lungs leading to a positive pressure breath. Removing the thumb from the outlet port allows the patient to exhale.



More complex are the valve-less systems, for example the different Mapleson arrangements. Here, once again, fresh gas arrives close to the patient's mouth, but the exhaled gas is delivered into the extended expiratory tubing and a reservoir bag. During expiration the fresh gas pushes the patient's CO_2-containing gas toward and into the breathing bag. The longer the expiratory pause, the more fresh gas will accumulate in the tubing and will thus be stored to be delivered to the patient with the next breath together with the continuously flowing oxygen. A 'pop-off valve' close to the bag lets the excess gas, likely to contain CO_2, escape. Observe that the system depends on the fresh gas flow to wash away previously exhaled gases and prevent rebreathing

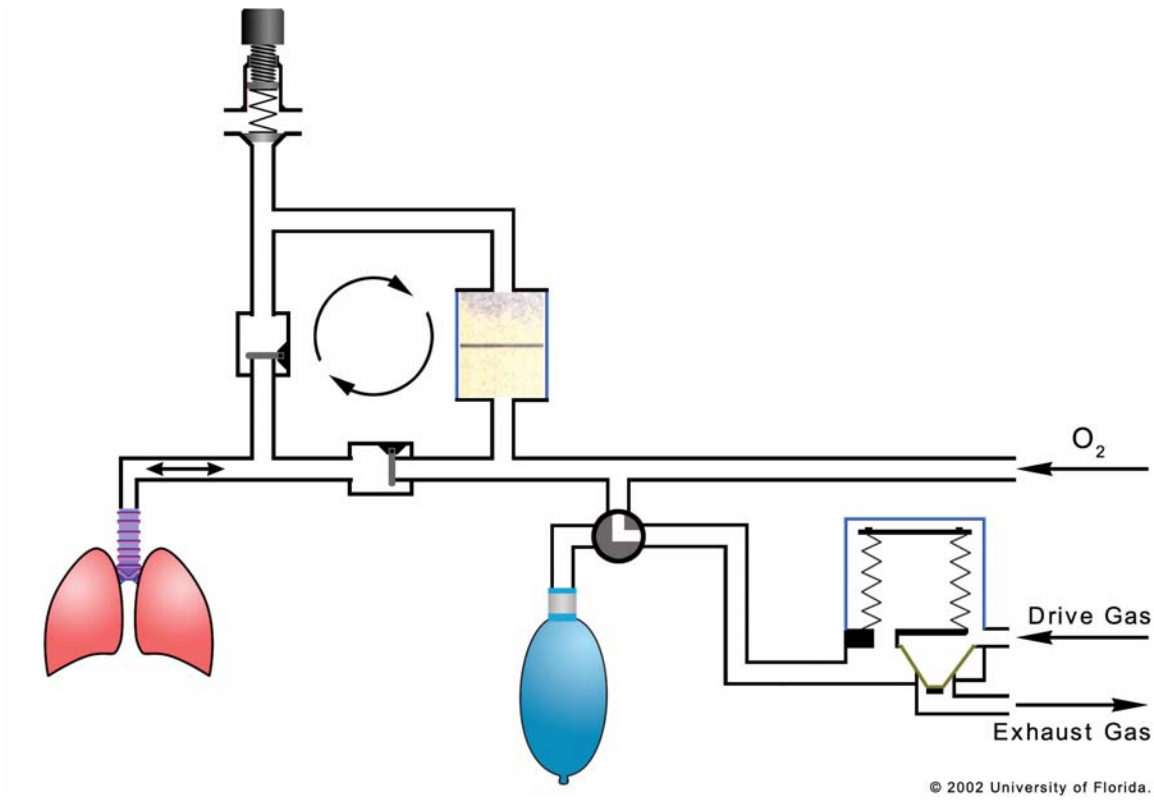


An alternative option relies on two valves. It enables storage of fresh gas during exhalation when the inspiratory valve closes. When the patient inhales, the expiratory valve closes and the patient inhales from the bag and the continuously flowing oxygen. The fresh gas flow must equal (or exceed) the patient's minute ventilation. When the fresh gas flow matches the patient's minute volume, no fresh gas is spilled. If the fresh gas exceeds the patient's minute volume, the excess gas escapes during exhalation. Of course, if the fresh gas flow were to exceed the patient's peak inspiratory flow rate, fresh gas would escape even during inspiration as well as expiration.

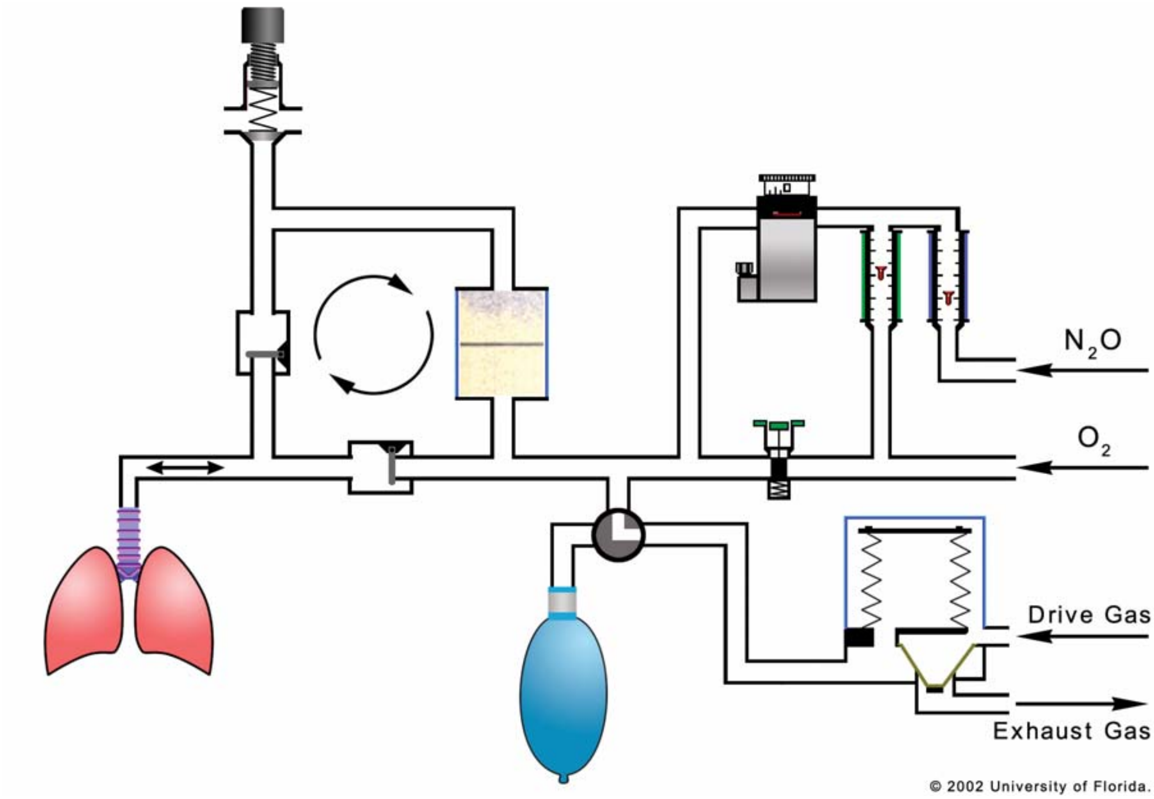


We tend to forget that all air-breathers (man and beast) rebreathe some of their exhaled gases. In anesthesia this becomes a gas-saving virtue, as long as we remove the carbon dioxide. Here the exhaled gas is brought back and added to the fresh gas. The system has formed a circle (in the diagram looking like a square!). The interposed carbon dioxide absorber removes the exhaled CO_2. Only the oxygen consumed by the patient must be added. A "pop-off" (venting) valve becomes necessary if more than the required oxygen is added to the system. This spring-loaded valve is formally known as the Adjustable Pressure Limiting (APL) valve. When it is partially closed, it enables us to build up pressure in the system and thus in the patient's lungs. This is important during manual ventilation when enough pressure must be developed in the system to inflate the patient's lungs.

Observe that the pop-off valve will spill gas rich in CO_2 rather than fresh gas.

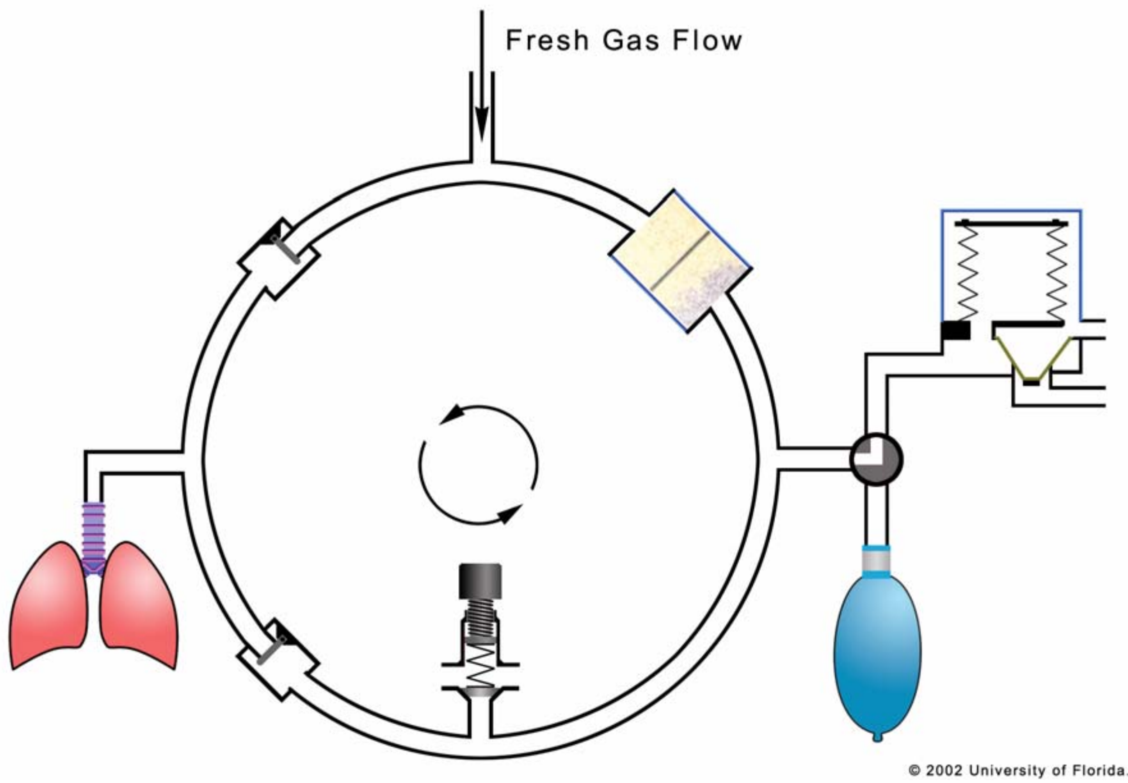


With manual ventilation the pop-off valve must be partially closed so that enough pressure can be generated to inflate the patient's lungs. Thus, excess gas can only escape during inspiration, when the pressure in the system is adjusted to inflate the lung and vent excess gas. This can cause trouble when resistance in the endotracheal tube gradually increases as can occur in pediatric tubes with inspissated sputum. More and more pressure will be required to overcome the growing resistance, more and more gas is vented, and less and less is delivered to the patient. A ventilator can be added as a parallel system to the reservoir (breathing) bag. However, in this arrangement, the pop-off valve would have to be closed so that it does not create a leak during mechanical ventilation. During mechanical ventilation the excess gas is vented late in expiration – as is also true with spontaneous ventilation.



Gases other than oxygen can be admitted to the system.

And a vaporizer can be included as well as an oxygen flush that bypasses the vaporizer when delivering large flows of O_2 into the circuit



A useful conceptual summary of an anesthesia breathing circuit is shown here. During inspiration, the expiratory valve closes and during expiration, the inspiratory valve is closed. Since fresh gas flow continues throughout the respiratory cycle, the fresh gas flowing into the system during expiration will be forced to flow in the direction of the CO_2 absorber, only to be inspired during the next inspiratory cycle.

Several different gas delivery and ventilator and breathing systems have been developed. Whatever their design, the system must meet the conditions listed in the mission objectives.

Part 2. How the Virtual Anesthesia Machine (VAM) simulation works

This APSF workbook contains a tutorial on using the Virtual Anesthesia Machine (VAM) simulation (v 8.33) at http://www.anest.ufl.edu/vam. The tutorial explains how to use the VAM simulation and what controls users can adjust. This tutorial is also supplemented with an on-line tutorial at http://www.anest.ufl.edu/~eduweb/vam/VAMtutorial.html.

A static screenshot of the VAM simulation screen overlaid with a map-like coordinate grid helps users locate clickable icons and text on the simulation screen.

Input

Users can interact with the following in version 8.33 of the VAM simulation by clicking with a pointing device. Visual, and in certain cases audible, feedback is provided upon clicking on an interactive icon to cue users that the requested intervention has been performed.

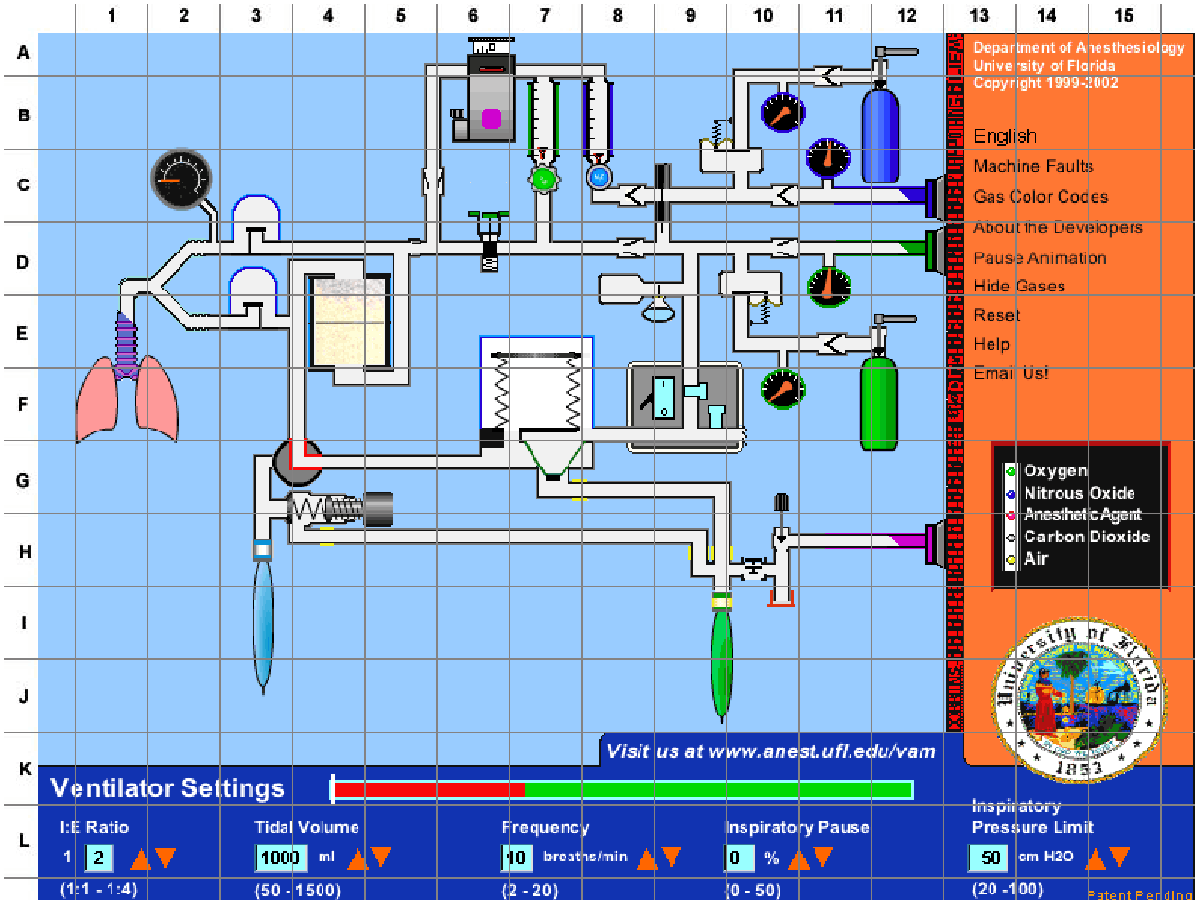
1. O_2 pipeline connection (connected/disconnected)
2. N_2O pipeline connection (connected/disconnected)
3. O_2 cylinder post valve (open/closed)
4. N_2O cylinder post valve (open/closed)
5. O_2 flow meter knob (click and drag clockwise to decrease flow and in other direction to increase flow)
6. N_2O flow meter knob (click and drag clockwise to decrease flow; in other direction to increase flow)
7. O_2 flush button (on/off)
8. Vaporizer concentration dial knob (on/off)
9. Vaporizer filler cap (on/off)
10. Airway pressure gauge size (minimized/maximized for legible pressure readings)
11. Selector knob (Mechanical ventilator/Breathing bag)
12. Breathing bag (click to squeeze bag and deliver a manual breath)
13. APL ("pop-off") valve (fully closed, just right, fully open)
14. Ventilator switch (on/off)
15. Scavenging vacuum adjustment valve (fully closed, just right, fully open)
16. Scavenging vacuum pipeline connection (connected/disconnected)
17. I:E ratio of ventilator (1:1 to 1:4 in increments of 1; default 1:2)
18. Set tidal volume (50 – 1500 mL in increments of 50 mL; default 1,000 mL)
19. Set frequency (2 – 20 breaths/min in increments of 2 bpm; default 10 bpm)
20. Inspiratory pause (0 – 50% of inspiratory time in increments of 5%; default 0)
21. Inspiratory pressure limit (20 – 100 cm H_2O in increments of 1 cm H_2O; default 50 cm H_2O)
22. Language selection (Arabic, Chinese, Dutch, English, French, German, Italian, Korean, Russian, Spanish)
23. Choice of triggering machine faults (select between 2 machine faults)
24. Gas color code (US/ISO)
25. About the developers (Lists the names of VAM team members)
26. Pause animation/Resume animation
27. Hide gases/Show gases
28. Reset the simulation to start simulation afresh with default settings and without carryover from prior interventions
29. Help (links to an animated tutorial on how to use the VAM simulation)
30. Email us! (a link to provide feedback via email)

Output

In version 8.33 of the Virtual Anesthesia Machine, users can observe the following in order to develop an overall understanding of 1) how a traditional anesthesia machine functions and 2) the interactions between different components.

1. Color of O_2 molecules
2. Rate of displacement of O_2 molecules (an indication of flow rate of O_2)
3. Color of N_2O molecules
4. Rate of displacement of N_2O molecules (an indication of flow rate of N_2O)
5. Color of molecules of volatile anesthetic agent
6. Rate of displacement of anesthetic agent molecules (an indication of flow rate of anesthetic agent)
7. Color of CO_2 molecules
8. Rate of displacement of CO_2 molecules (an indication of flow rate of CO_2)
9. Color of air molecules
10. Rate of displacement of air molecules (an indication of flow rate of air)
11. Needle on O_2 pipeline pressure gauge (50 psig/0 psig)
12. Needle on N_2O pipeline pressure gauge (50 psig/0 psig)
13. Needle on O_2 cylinder pressure gauge (2200 psig/0 psig)
14. Needle on N_2O cylinder pressure gauge (745 psig/0 psig)
15. Position of O_2-failsafe mechanism (C9) (open or closed)
16. O_2 flow meter bobbin position (multiple positions)
17. N_2O flow meter bobbin position (multiple positions)
18. Inspiratory valve leaflet position (closed/open)
19. Airway pressure gauge needle (pressure units can be read when gauge is maximized)
20. Lung size (multiple sizes including representation of lung barotrauma, mathematically modeled)
21. Expiratory valve leaflet position (closed/open)
22. Breathing bag size (many sizes; mathematically modeled)
23. Bellows position (many positions, mathematically modeled)
24. Ventilator relief valve (open/closed)
25. Ventilator proportional flow control valve (open/closed)
26. Ventilator exhalation valve (closed/open)
27. Scavenging bag size (many sizes, mathematically modeled)
28. Scavenging manifold positive pressure relief valve (closed/open)
29. Scavenging manifold vacuum (negative pressure) relief valve (closed/open)
30. Bellows leak (present/absent)
31. Numerical display of set Inspiratory:Expiratory ratio
32. Numerical display of set tidal volume
33. Numerical display of set breathing frequency
34. Numerical display of set inspiratory pause
35. Numerical display of set inspiratory pressure limit
36. A horizontal color-coded scroll bar at the bottom of the simulation providing graphical, color-coded indications of the phase of each mechanical breath. Active inspiration is coded red while inspiratory pause is yellow, and expiration is green.

VAM grid map



This grid map of the VAM simulation screen is used to provide the coordinates of the anesthesia machine icons in the subsequent exercises.

Part 3 Specific safety-related exercises using VAM

Patient Safety Disclaimer: While the emphasis in this educational module is necessarily about the anesthesia machine, it bears repeating over and over again that the anesthesia machine is only a means to an end, providing anesthesia to a patient. The primary responsibility of the anesthesia provider is to the patient, not to the anesthesia machine. Therefore, while it is generally agreed that it is good for anesthesia providers to understand machine function, it should be equally clear that if an anesthesia provider suspects a malfunction in the anesthesia machine, a safe response is to immediately switch to a self-inflating resuscitation bag and call for help. There is always the danger that the anesthesia provider shifts attention from the patient to debugging the anesthesia machine.

The format for the following specific learning objectives is standardized to provide consistency aimed at quickly getting oriented and finding the desired information.

a. List of high pressure system learning objectives

1. If the O_2 pipeline is connected and pressurized and the O_2 cylinder is opened, will an anesthesia machine be supplied with oxygen from the pipeline or the cylinder?

2. What does a cylinder pressure gauge read when a previously open full cylinder is closed with the associated pipeline supply connected?

3. What is the purpose of disconnecting the O_2 pipeline when attempting to read O_2 cylinder pressure?

4. If the O_2 cylinder is supplying O_2 to an anesthesia machine during failure of the O_2 pipeline supply, will O_2 from the cylinder flow out of the O_2 pipeline?

5. What happens to N_2O flow if the O_2 pipeline supply is interrupted?

6. After an O_2 "failsafe" device has been triggered by an O_2 supply failure and adequate O_2 supply pressure has been subsequently re-established, is the set O_2/N_2O ratio prior to the O_2 supply failure still retained?

7. If an O_2 cylinder is left open and the O_2 pipeline supply fails, will there be an audible alarm upon failure of the O_2 pipeline supply?

Question 1 – High pressure system. During an anesthetic, a young healthy ASA I patient with no pre-existing conditions suddenly begins to desaturate. You check the gas flows and observe that the oxygen and nitrous oxide flowmeters show correct settings. However, the oxygen analyzer shows falling concentrations of oxygen. You suspect that the gas supplied by the O_2 pipeline may not be oxygen. You open the reserve O_2 cylinder while leaving the O_2 pipeline connected. Will the patient's oxygen saturation improve? Which O_2 source will supply gas to the anesthesia machine, in general, in the above scenario?

Answer: The O_2 pipeline, in the United States

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Place cursor on O_2 flowmeter knob icon (C-7) – *O_2 flowmeter knob will zoom out*
c. Click and drag to rotate O_2 flowmeter knob icon counterclockwise ("lefty loosy; righty tighty") until O_2 bobbin is roughly in the middle of the flowmeter tube. *The pressure gauge on the O_2 cylinder pressure gauge (F-10) reads zero.*
d. Click on the O_2 cylinder post valve (E-12) to open the O_2 cylinder – *O_2 molecules do not flow out of the cylinder; O_2 molecules continue flowing out of the O_2 pipeline. The needle on the O_2 cylinder pressure gauge (F-10) reads full indicating cylinder is full.*

Explanation: The O_2 pipeline pressure is nominally 45 – 55 psig whereas the pressurized O_2 in the cylinder (2,200 psig when full) is regulated down to 40 psig by the O_2 cylinder pressure regulator (D-10, E-10). Thus, the higher pressure in the O_2 pipeline will prevent flow from the O_2 cylinder as long as the O_2 pipeline pressure is above the down-regulated O_2 cylinder pressure, i.e., 40 psig. Conversely, if the O_2 pipeline pressure falls below the down-regulated cylinder pressure, O_2 will be supplied from the opened cylinder. A disconnected O_2 pipeline is at a pressure of 0 psig and will allow O_2 from the cylinder to flow. Click on the O_2 pipeline connector (D-12) to disconnect it and watch the O_2 molecules flow from the open O_2 cylinder. Note that the O_2 pipeline pressure gauge (D-11) reads zero verifying that the O_2 pipeline has been disconnected.

Learning objectives:

1. The O_2 pipeline has to be disconnected or at a supply pressure lower than the down-regulated cylinder pressure (nominally 40 psig) for O_2 to flow from an open O_2 cylinder.

Question 2 – High pressure system. During the morning pre-use check of an anesthesia machine, you open the O_2 cylinder to check the O_2 cylinder pressure. The O_2 cylinder reads full (2,000 psig). You subsequently close the O_2 cylinder. With the anesthesia machine turned on with a minimal flow of 300 ml/min of O_2, what does the O_2 cylinder pressure gauge now read with the O_2 pipeline supply connected and the O_2 cylinder closed?

Answer: Even though the O_2 cylinder has been closed, the O_2 cylinder pressure gauge will continue to read full.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions – *O_2 cylinder pressure gauge (F-10) reads zero*
b. Click on the O_2 cylinder post valve (E-12) to open the O_2 cylinder - *O_2 cylinder pressure gauge (F-10) reads full*
c. Click on the O_2 cylinder post valve (E-12) to close the O_2 cylinder - *O_2 cylinder pressure gauge (F-10) reads full*

Explanation: With the O_2 pipeline connected, any O_2 demand, including the minimal O_2 flow of 300 ml/min (if present), will be supplied by the pipeline, not the pressurized O_2 trapped in the piping (E-10 and E-11) between the closed cylinder and the pressure regulator (D-10). The trapped O_2 does not flow. Because of the location of the O_2 cylinder pressure gauge (F-10), the displayed pressure on the O_2 cylinder pressure gauge is the pressure of the O_2 that was trapped in piping (E-10 and E-11) when the O_2 cylinder was closed. Therefore, the displayed pressure on the O_2 cylinder pressure gauge does not drop to zero when an O_2 cylinder is closed, as one would intuitively expect. To depressurize the O_2 cylinder pressure gauge, the O_2 pipeline connector (D-12) must be disconnected while there exists an O_2 demand (e.g., an O_2 flush, a non-zero O_2 flow set via the O_2 flowmeter or the minimal 300 ml/min O_2 flow if present).

Learning objectives:

1. A cylinder pressure gauge will retain the last displayed pressure when a cylinder is closed as long as the system is connected to a pressurized pipeline.
2. A cylinder pressure gauge reading full does not mean that the corresponding cylinder is open.
3. To depressurize a cylinder pressure gauge displaying a non-zero value, disconnect the corresponding pipeline supply and create a demand of the corresponding gas, e.g., by creating an outflow of gas using the corresponding flowmeter knob. This applies for both an O_2 and an N_2O cylinder pressure gauge.

Question 3 – High pressure system. You have been taught that "the O_2 pipeline must be disconnected to obtain an accurate O_2 cylinder pressure reading". You walk into the OR to perform the morning pre-use check of the anesthesia machine you will be using today. The O_2 pipeline is connected and the O_2 pipeline pressure gauge reads 50 psig. The O_2 cylinder pressure gauge reads zero. The O_2 pipeline connector is very hard to reach behind stacks of heavy equipment. Do you "wing it" or do you disconnect the O_2 pipeline to read the O_2 cylinder pressure?

Answer: Neither. Trick question.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

O_2 cylinder pressure gauge already displaying zero

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions – *O_2 cylinder pressure gauge (F-10) reads zero*
b. Click on O_2 pipeline connector icon (D-12) to disconnect O_2 pipeline. *O_2 cylinder pressure gauge (F-10) still reads zero*

O_2 cylinder pressure gauge displaying a non-zero reading

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions – *O_2 cylinder pressure gauge (F-10) reads zero*
b. Click on O_2 cylinder post valve icon (E-12) to open O_2 cylinder - *O_2 cylinder pressure gauge (F-10) now reads full (non-zero)*
c. Click on O_2 cylinder post valve icon (E-12) to close O_2 cylinder - *O_2 cylinder pressure gauge (F-10) still reads full*
d. Click on O_2 pipeline connector icon (D-12) to disconnect O_2 pipeline. *O_2 cylinder pressure gauge (F-10) reads zero*

Explanation: The purpose of disconnecting the O_2 pipeline is to depressurize the O_2 cylinder pressure gauge to get rid of a retained non-zero cylinder pressure reading and make it display zero. Because the O_2 cylinder pressure gauge is already reading zero, there is no need anymore to disconnect the O_2 pipeline. And you are not "winging it" and taking a risk by not disconnecting the O_2 pipeline. If the O_2 cylinder pressure gauge is already displaying zero, you will obtain an accurate cylinder pressure reading when you open the O_2 cylinder without disconnecting the pipeline.

Learning objectives:

1. The O_2 pipeline does not need to be disconnected to get an accurate O_2 cylinder pressure reading if the O_2 cylinder pressure gauge is already displaying zero.
2. Disconnecting an O_2 pipeline when the O_2 cylinder pressure gauge is displaying a non-zero value will depressurize the cylinder pressure gauge.

Question 4 – High pressure system. During a case, the O_2 pipeline supply has failed. You open the O_2 cylinder and continue the case. In addition to O_2 from the cylinder flowing to the anesthesia machine, will it also flow retrograde into the O_2 pipeline and prematurely exhaust the O_2 cylinder?

Answer: No

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag icon for O_2 flowmeter control knob (C-7) until bobbin is halfway up the O_2 flowmeter tube
c. Click on O_2 pipeline connector icon (D-12) to simulate O_2 pipeline failure *Pipeline O_2 pressure gauge (D-11) displays zero pressure. Residual O_2 molecules flow out of O_2 pipeline and check valve (D-10) on O_2 pipeline closes to prevent retrograde flow into O_2 pipeline.*
d. Click on O_2 cylinder post valve icon (E-12) to open O_2 cylinder. *Cylinder O_2 pressure gauge (F-10) displays pressure corresponding to a full cylinder. Gases flow from O_2 cylinder to supply the anesthesia machine. The O_2 pipeline check valve (D-10) is closed preventing back flow of O_2 in the O_2 pipeline.*

Explanation: O_2 pipelines are fitted with a check valve that prevents retrograde flow of O_2 into the O_2 pipeline. This is also applicable to other gases supplied by pipeline to an anesthesia machine such as N_2O and air. See N_2O check valve (C-10) in VAM simulation.

Learning objectives:

1. Gas (O_2. N_2O, air, others) from a reserve cylinder will not flow retrograde into a pipeline because of the check valve fitted on a pipeline.
2. The check valve will prevent retrograde flow whether the pipeline is plugged into a central outlet or not.

Question 5 – High pressure system. You are in the middle of a case with a fresh gas flow (FGF) set at 3.5 L/min N_2O and 1.5 L/min O_2. The O_2 pipeline supply fails. You eventually diagnose the problem and walk to the back of the anesthesia machine and open the reserve O_2 cylinder. In the time interval between the O_2 pipeline failing and opening the O_2 cylinder, did the anesthesia machine deliver a FGF of 3.5 L/min N_2O and 0 L/min O_2, i.e., was the delivered gas mixture 100% N_2O?

Answer: No

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag icon for O_2 flowmeter control knob (C-7) until bobbin is one third up the O_2 flowmeter tube
c. Click and drag icon for N_2O flowmeter control knob (C-8) until bobbin is two third up the N_2O flowmeter tube
d. Click on O_2 pipeline connector icon (D-12) to simulate O_2 pipeline failure. *The "O_2 failsafe device" icon (C-9) is activated by the loss in O_2 supply pressure and shuts off the flow of N_2O to prevent delivery of a hypoxic gas mixture.*

Explanation: The O_2 supply pressure is used to lift the "O_2 failsafe" device into a position where it allows N_2O flow. Absence of sufficient O_2 supply pressure will cause the "O_2 failsafe" device to drop to a position where it shuts off flow of N_2O and other anoxic gases. Some older Dräger Narkomed machines did not shut off helium but did shut off air (technically not an anoxic gas because it contains 21% O_2), upon loss of O_2 supply pressure.

Learning objectives:

1. Anesthesia machines are designed to shut off the flow of anoxic gases such as N_2O if the O_2 supply pressure fails.
2. Generally, the flow of air is not shut off in the case of O_2 supply failure.

Question 6 – High pressure system. You are in the middle of a case with a fresh gas flow (FGF) set at 3.5 L/min N_2O and 1.5 L/min O_2. The O_2 pipeline supply fails. The "O_2 failsafe device" cuts off the flow of N_2O. With the help of the audible alarm that sounds, you correctly diagnose the problem and walk to the back of the anesthesia machine and open the reserve O_2 cylinder. O_2 supply pressure is re-established to the anesthesia machine. N_2O flow is allowed again. Will the previous settings you set earlier for the fresh gas flow be retained or will you have to re-dial the O_2 and N_2O settings?

Answer: The previous O_2/N_2O settings will be retained.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag icon for O_2 flowmeter control knob (C-7) until bobbin is one third up the O_2 flowmeter tube
c. Click and drag icon for N_2O flowmeter control knob (C-8) until bobbin is two third up the N_2O flowmeter tube
d. Click on O_2 pipeline connector icon (D-12) to simulate O_2 pipeline failure. *The "O_2 failsafe device" icon (C-9) is activated by the loss in O_2 supply pressure and shuts off the flow of N_2O to prevent delivery of a hypoxic gas mixture. First the N_2O and then the O_2 flowmeter bobbin drop to zero, indicating that no gas is flowing in the respective flowmeter.*
e. Click on O_2 cylinder post valve icon (E-12) to open O_2 cylinder. *The O_2 and N_2O flowmeter bobbins float back to their previous settings.*

Explanation: The "O_2 failsafe" device does not change the settings for the N_2O flowmeter even though it may appear to do so. It simply cuts off the supply of N_2O to the N_2O flowmeter leaving the actual N_2O flowmeter setting unmodified.

Learning objectives:

1. Previously dialed N_2O and O_2 flowmeter settings are retained after activation of an "O_2 failsafe" device caused by an O_2 supply failure and subsequent re-establishment of gas flow.

Question 7 – High pressure system. Upon performing a pre-use check of your anesthesia machine, the O_2 cylinder pressure reads full. You forget subsequently to close the O_2 cylinder and start your case. In the middle of your case, the O_2 pipeline supply fails. Will there be an audible alarm to warn you that the O_2 pipeline supply has failed?

Answer: No.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click on O_2 cylinder post valve icon (E-12) to open O_2 cylinder.
c. Click on O_2 pipeline connector icon (D-12) to simulate O_2 pipeline failure. *The audible alarm does not sound.*
d. Click O_2 cylinder post valve icon (E-12) to close O_2 cylinder and simulate O_2 cylinder exhaustion. *The audible alarm sounds.*

Explanation: The audible alarm device (D-9 and E-9) is activated when the O_2 supply pressure drops below a set threshold (approximately 26 psig). If the O_2 cylinder is left open, O_2 will start flowing from the cylinder as soon as the pressure in the pipeline falls below 40 psig and will prevent the O_2 supply pressure from falling below 40 psig. The audible alarm will sound when the O_2 cylinder is depleted.

Learning objectives:

2. There will be no audible warning of O_2 pipeline supply failure if the O_2 cylinder is left open.
3. When the audible alarm does sound upon eventual cylinder exhaustion, there will be no O_2 supply at all (assuming a single O_2 cylinder anesthesia machine).

Post-test questions – High pressure system

1. If you close an O_2 cylinder and press the O_2 flush button to depressurize the O_2 cylinder pressure gauge while the O_2 pipeline is connected, what will be the resulting reading on the O_2 cylinder pressure gauge?

2. Why does the O_2 pipeline have to be disconnected, in certain instances, to obtain a correct O_2 cylinder pressure reading?

3. Do you always have to disconnect the O_2 pipeline to read the O_2 cylinder pressure correctly if the O_2 cylinder pressure gauge is displaying a non-zero value?

4. Failure of the O_2 pipeline supply activates the "O_2 failsafe" device and cuts off N_2O flow. What happens to N_2O flow in the case of failure of the O_2 cylinder supply?

5. When will there be an audible alarm if a full O_2 cylinder is left open and the O_2 pipeline supply is subsequently interrupted or fails?

6. Which N_2O source is used if the pipeline N_2O supply is connected and pressurized and the N_2O cylinder is open?

b. List of low pressure system learning objectives

1. Does the O_2 flow triggered by an O_2 flush flow through a vaporizer?

2. With the O_2 flow meter at its minimum setting, will a hypoxic gas mixture result at the common gas outlet if N_2O flow is increased to its maximum setting?

3. Do the gases from the flow meters continue to flow into the breathing circuit during inspiration?

4. Does the amplitude of the fresh gas flow affect delivered tidal volume?

5. Is the internal space inside a vaporizer in pneumatic connection with the rest of the anesthesia machine when its concentration dial is set to 0?

Question 1 – Low pressure system. During a case using low-flow anesthesia (total FGF of about 0.5 L/min), your patient appears to be light after you have suctioned secretions out of the endotracheal tube. Upon reconnecting the patient back to the breathing circuit, you initiate an O_2 flush to replenish the gas volume lost while the circuit was open to atmosphere during suctioning. Concerned about the patient being light, you simultaneously increase the vaporizer setting while flushing the circuit. Does your patient receive a clinically significant increase in inspired anesthetic concentration during the O_2 flush as a result of the increase in vaporizer concentration setting?

Answer: No.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press “Reset “ (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click on vaporizer concentration dial icon (A-6) to switch vaporizer to a non-zero setting. *The external view of the vaporizer fades into a cut-out view when the cursor is placed on the vaporizer icon. FGF molecules flow over the liquid anesthetic pool inside the vaporizer and pick up vaporized anesthetic molecules.*
c. Press the O_2 flush icon (D-6). *The flow of O_2 molecules caused by pressing the O_2 flush flows directly into the breathing circuit without passing through the vaporizer. The molecules from the O_2 and N_2O flowmeters continue to flow into the breathing circuit during an O_2 flush.*

Explanation: The high O_2 flow (approx. 60 L/min) generated by an O_2 flush does not flow through the vaporizer and is thus at a volatile anesthetic concentration of 0%. The O_2 flush thus dilutes the anesthetic concentration in the breathing circuit.

Learning objectives:
1. Flow from an O_2 flush bypasses the vaporizer.
2. Fresh gas inflow caused by an O_2 flush is of the order of 60 L/min.
3. The FGF continues to flow into the breathing circuit during an O_2 flush.

Question 2 – Low pressure system. You wish to deliver 3.5 L/min nitrous oxide with oxygen. Should you first set the nitrous oxide flow, relying on the proportioning ("hypoxic guard") device that will automatically increase the oxygen flow rate, assuring 25% oxygen?

Answer: No.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions

b. Click and drag the N_2O flowmeter knob icon (C-8) counterclockwise until the N_2O bobbin is 2/3 up the N_2O flowmeter tube. *The O_2 flowmeter bobbin is observed to go up and accompany the N_2O flowmeter bobbin goes past a given flow.*

Explanation: A hypoxic guard mechanism functions to increase O_2 flow or decrease N_2O flow so that the set O_2 concentration is never below a given value such as 25%. Depending on the manufacturer, the hypoxic guard mechanism is either mechanically or pneumatically implemented.

Learning objectives:

1. Anesthesia machines in the United States are equipped with a "hypoxic guard" mechanism that ensures that, irrespective of user error in setting the gas mixture, the set O_2 concentration cannot be less than 25%.
2. Do not rely on the hypoxic guard mechanism which has been known to fail. Always start by dialing O_2 first in the event that the "hypoxic guard" mechanism is defective.

Question 3 – Low pressure system. Do the gases from the flow meters continue to flow into the breathing circuit during mechanical inspiration?

Answer: Yes

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press “Reset “ (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag the O_2 flowmeter knob icon (C-7) counterclockwise to increase O_2 flow until the bobbin is halfway up the flowmeter tube.
c. Click on ventilator “On/off” switch icon (F-9) to turn on ventilator. *During mechanical inspiration (bellows travelling down in the simulation), gas molecules continue to flow out of the flowmeters and enter the circuit.*

Explanation: The gas flowmeter tubes are purely mechanical devices in traditional anesthesia machines. The flow output, once set by the user, is continuous and is not interrupted during mechanical inspiration.

Learning objectives:
1. Gas flows continuously out of the flowmeters into the breathing circuit during all phases of all modes of ventilation. This may have clinical consequences.

Question 4 – Low pressure system. You are ventilating a pediatric patient with the following ventilator settings: tidal volume of 50 mL, a rate of 20 bpm and an I:E ratio of 1:1 using a low flow technique (total FGF of 0.5 L/min). The surgical procedure has concluded. The operation ended earlier than expected and the patient is still partially paralyzed needing ventilation while lightening anesthesia. You turn off the vaporizer and turn up the fresh gas flow to the maximum O_2 setting to wash out the volatile anesthetics while leaving the ventilatory parameters (VT, RR, I:E) unmodified. Does this last maneuver (increasing the FGF) affect the delivered tidal volume?

Answer: Yes

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click on the O_2 flush button icon (D-6) to initiate an O_2 flush to fill the bellows
c. Click on the ventilator "On/off" switch icon (F-9) to turn on the ventilator. *During mechanical inspiration, very few gas molecules from the flowmeters flow in the piping at D-3, D-4, D-5 at low fresh gas flow.*
d. Click on the airway pressure gauge icon (C-2) to zoom out the airway pressure gauge. *The peak inspiratory pressure (PIP) is about 15 cm H_2O. The size of the lung icon (F-1 and F-2) at peak inflation is normal.*
e. Click and drag the O_2 flowmeter knob icon (C-7) counterclockwise until the O_2 bobbin is at its maximum setting. *The PIP increases to 20 cm H_2O and the size of the lung icon at peak inflation increases (a subtle change). More gas molecules are seen to flow towards the patient at piping at D3, D4, D5 at high fresh gas flow compared to low fresh gas flow.*

Explanation: Fresh gas flows continuously into the breathing circuit, including during mechanical inspiration. The product of the fresh gas flow (FGF) times the inspiratory time (Ti) corresponds to the augmentation of the tidal volume by FGF. VT (delivered) = VT (set) + (FGF * Ti)

Learning objectives:

1. During mechanical ventilation, fresh gas flow (FGF) affects (both augments or reduces with increased or decreased FGF respectively) the delivered tidal volume in traditional anesthesia machines.

Question 5 – Low pressure system. You are performing a low pressure leak check according to the 1993 FDA anesthesia machine pre-use check recommendations on an anesthesia machine equipped with only an isoflurane vaporizer. The concentration dial of the vaporizer is set to 0. You disconnect the fresh gas flow hose from the common gas outlet and repeatedly squeeze the suction bulb and then release. The suction bulb stays deflated for 10 seconds. Have you established that the isoflurane vaporizer has no leaks?

Answer: No

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag O_2 flowmeter knob icon (C-7) until O_2 bobbin is halfway up the tube to generate sufficient gas flow
c. Place the cursor on the vaporizer icon (A-6 and B-6). *The view of the vaporizer fades from an external view to a cut-out view which clearly shows that part of the internal space inside the vaporizer is not in pneumatic connection with the rest of the circuit.*
d. Click on the vaporizer concentration dial icon (A-6). *The internal space inside the vaporizer is now in pneumatic connection with the circuit.*

Explanation: The internal space inside a vaporizer is not in pneumatic connection with the rest of the anesthesia machine when its concentration dial is set to 0.

Learning objectives:

1. To properly perform a low pressure leak check on a vaporizer, the vaporizer must be in pneumatic connection with the evacuated suction bulb attached to the common gas outlet, i.e., the vaporizer concentration dial must be at a non-zero setting.

Post-test questions – Low pressure system

1. If a vaporizer concentration dial is adjusted to a non-zero setting, will O_2 flow generated by an O_2 flush flow through the vaporizer?

2. With the N_2O flow meter at its maximum setting, will a hypoxic gas mixture result at the common gas outlet if the O_2 flow meter is decreased to its minimum setting?

3. Will liquid anesthetic spill from a loose filler cap if the vaporizer concentration dial is set to 0?

4. How do non-electronic, variable bypass vaporizers such as isoflurane vaporizers work?

5. During positive pressure ventilation, will liquid anesthetic spill from a loose filler cap if the vaporizer concentration dial is at a non-zero setting?

c. List of breathing circuit learning objectives

1. Why are there two gas exit ports instead of only one?

2. Are the gases exhaled by a patient scrubbed of CO_2 before entering the bellows during mechanical ventilation?

3. What is the function of the selector valve?

4. What is the flow path of the fresh gas from the common gas outlet during expiration?

5. Does a gas concentration set at the flowmeters immediately result in an identical inspired gas concentration?

Question 1 – Breathing circuit. How many exit ports for excess gas does the circle breathing system design contain?

Answer: 2

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag the O_2 flowmeter control knob icon (C-7) counterclockwise until the O_2 bobbin is halfway up the tube
c. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator. *Excess gas leaves the circuit via the ventilator pressure relief ("pop-off") valve (G-7) during end-exhalation after the bellows has been refilled.*
d. Optional. Click on the ventilator on/off switch icon (F-9) to turn off the ventilator.
e. Click on the selector knob icon (G-4) to select manual ventilation.
f. Click on the breathing bag icon (I-3) to squeeze the bag and deliver a manual breath. *Excess gas leaves the circuit via the APL valve outlet during the beginning of manual inspiration or when the pressure inside the circuit exceeds the adjustable pressure threshold set on the APL valve.*

Explanation: Two exit ports are required instead of one because the manual and mechanical ventilation systems are mutually exclusive redundant systems in a traditional anesthesia machine. Each mutually exclusive system must have its own exit port to exhaust excess gas.

Learning objectives:
1. The APL valve outlet is the exit port for excess gas during manual ventilation
2. The ventilator relief valve outlet is the exit port for excess gas during mechanical ventilation
3. Gas leaves the circuit during inspiration in manual ventilation
4. Gas leaves the circuit during end-expiration, after the bellows has filled, during mechanical ventilation
5. Gas leaves the system at the end of expiration, when the bag is full, during spontaneous ventilation.

Question 2 – Breathing circuit. Are the gases exhaled by a patient scrubbed of CO_2 before entering the bellows during mechanical ventilation?

Answer: No

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag the O_2 flowmeter control knob icon (C-7) counterclockwise until the O_2 bobbin is halfway up the tube
c. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator.
d. *During exhalation, exhaled gases flow directly from the exhalation valve (E-3) to the bellows (F-7) without passing through the CO_2 absorber (E-4).*
e. *During inspiration, CO2 containing gas from the bellows is pushed through the CO2 absorber on its way towards the patient.*

Explanation: During mechanical ventilation, gases exhaled by the patient flow directly to the bellows during exhalation. The CO_2 absorber is located so that exhaled gases are only scrubbed clean of CO_2 when they are being redirected to the patient. Scrubbing exhaled gases that may then be dumped into the scavenging system would prematurely exhaust the CO_2 absorbent and be wasteful.

Learning objectives:

1. Exhaled gas entering the bellows is not scrubbed free of CO_2
2. Exhaled gas being redirected towards the patient during inspiration passes through the CO_2 absorber and is scrubbed free of CO_2.

Question 3 – Breathing circuit. During manual ventilation, you have adjusted the APL (Adjustable Pressure Limiting) valve, also known as the "pop-off" valve, to relieve pressures exceeding 25 cm H_2O. You have now switched to mechanical ventilation. The surgeon puts a pack into the abdomen, pushing up the diaphragm. You need a higher peak inspiratory pressure (PIP) to deliver the same tidal volume. Will the set APL valve setting interfere with your ability to deliver the required tidal volume to maintain CO_2 at an appropriate level?

Answer: No (in most machines – see explanation)

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click on the airway pressure gauge icon (C-2) to zoom out the gauge.
c. Click on the selector knob icon (G-4) to select manual ventilation
d. The default APL valve setting (upon reset of the VAM simulation) is 25 cm H_2O. Optionally, you can click on the APL valve icon (G-5) to step the APL valve through the 3 discrete settings (closed, 25 cm H_2O, open) simulated on the VAM simulation
e. Click and hold on the O_2 flush valve icon (D-6) to initiate and maintain an O_2 flush until the APL valve opens and the pressure plateaus at 25 cm H_2O
f. Click on the selector knob icon (G-4) to select mechanical ventilation. *Gas flow is diverted to the bellows.*
g. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator. *Gas does not escape through the APL valve set at 25 cm H_2O because it is effectively removed from the circuit when the selector knob is set to mechanical ventilation.*

Explanation: The selector valve is used to select between either the manual ventilation subsystem or the mechanical ventilation subsystem, in a mutually exclusive fashion. In the Ohmeda Modulus I and other designs where the APL valve remains in pneumatic connection with the rest of the circuit when the selector knob is set to mechanical ventilation, an APL valve setting of 20 cm H_2O will leak gas when the pressure in the circuit exceeds 20 cm H_2O. In these particular machines, an APL valve left open will therefore interfere with the minute volume delivered during mechanical ventilation.

Learning objectives:

1. The APL valve is excluded in most anesthesia machines when the selector valve knob is in the mechanical ventilation position
2. In the Ohmeda Modulus I and other designs where the APL valve remains in pneumatic connection with the rest of the circuit when the selector knob is set to mechanical ventilation, the APL valve has to be closed (turned fully clockwise) so that it does not create a leak during mechanical ventilation.

Question 4 – Breathing circuit. What is the flow path of the fresh gas from the common gas outlet during expiration?

Answer: The fresh gas from the flowmeter bank flows "backwards" through the CO_2 absorber and on to the bellows (if the flow is of sufficient amplitude) during expiration.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag the O_2 flowmeter knob icon (C-7) counterclockwise until the bobbin is halfway up the tube
c. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator. *Fresh gas flows backwards through the CO_2 absorber and mixes with exhaled gas from the patient on its way to the bellows.*

Explanation: During exhalation, the inspiratory valve (C-3) is closed. The path of least resistance for the fresh gas is via the absorber to the bellows and (if fresh gas flow is really excessive) and on to the scavenging system.

Learning objectives:

1. Gas flow from the flowmeter bank is continuous and has to flow somewhere
2. Gas flow follows the path of least resistance

Question 5 – Breathing circuit. You are using a minimal flow technique with a total FGF of 0.6 L/min (300 ml/min O_2 and 300 ml/min N_2O). Without changing the oxygen flow, you turn off the N_2O flow in preparation for emergence. Is your patient now inhaling gas with 0% N_2O?

Answer: No, not for a while

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag the N_2O flowmeter knob icon (C-8) counterclockwise until the N_2O bobbin is approximately at the same level as the O_2 bobbin
c. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator. Wait about 30 seconds to let the N_2O molecules reach the lungs and bellows
d. Click and drag the N_2O flowmeter knob icon (C-8) fully clockwise until there is no more N_2O molecules flowing in the N_2O flowmeter. *N_2O molecules are still recirculating in the circuit a long time after the N_2O flow has been reduced to zero.*

Explanation: Breathing circuits have a time constant whereby a change in the set gas composition does not immediately result in a corresponding change in the inspired gas composition. The time constant is influenced, among others, by the magnitude of the fresh gas flow and the volume of the breathing circuit.

Learning objectives:

1. A change in the set gas composition does not immediately result in a corresponding change in the inspired gas composition, especially at fresh flow rates less than minute ventilation
2. Breathing circuits exhibit a time constant in their response to changes in the set gas or volatile anesthetic concentration

Post-test questions - Breathing circuit

1. Does setting a non-zero vapor concentration at the vaporizer immediately result in an identical inspired vapor concentration?

2. Does setting a zero vapor concentration at the vaporizer immediately result in a zero inspired vapor concentration?

3. What is the purpose of the inspiratory valve (C-3)?

4. What is the purpose of the expiratory valve (E-3)?

5. Does the bellows contain CO_2?

6. Is gas flow in the CO_2 absorber bi-directional?

7. Does setting the N_2O flowmeter to 0 L/min immediately result in an inspired N_2O concentration of 0?

8. How do you set the knob for the selector valve during spontaneous ventilation?

9. Repeat the exercise in question 5 of the breathing circuit section and after step d, increase the O_2 flow to its maximum setting. What do you observe?

d. List of manual ventilation learning objectives

1. What would be the maximum pressure developed with the selector knob set to “Bag”, a fully closed APL valve and a high FGF, i.e., O_2 flow set to maximum?

2. During manual ventilation, when does excess gas exit the breathing circuit and enter the scavenging system?

Question 1 – Manual ventilation. You earlier closed off the APL valve when you switched to mechanical ventilation during the maintenance phase. You are now getting ready for emergence. You have set the O_2 flow to maximum and set the selector knob to manual ventilation when you get paged. Distracted by the page, you forget to adjust the APL valve and squeeze the bag. What happens to the airway pressure?

Answer: It gradually increases until it plateaus at about 40 – 50 cm H_2O.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click on the APL valve icon (G-5) three (3) times until it is fully closed (spring coils are tightly compressed)
c. Click on the airway pressure gauge icon (C-2) to enlarge the gauge
d. Click and drag the O_2 flowmeter knob icon (C-7) counterclockwise until the O_2 bobbin is fully up
e. Click on the selector knob icon (G-4) to select manual ventilation. *The breathing bag (I-3) starts to swell. Pressure gradually rises and plateaus at 40 cm H_2O. The lungs become over-inflated and display a stylized representation of barotrauma*
f. After the pressure has reached 40 cm H_2O, click on the APL valve icon to partially open it. *The pressure drops to about 16 cm H_2O.*

Explanation: An APL valve is, in general, a pressure threshold device. Older Dräger Narkomed machines used a variable resistance APL device. A fully-closed contemporary APL valve, such as the one shown in the VAM simulation, will have a fully compressed spring pushing against the back of a diaphragm such that the APL valve will only let gas flow through it when pressure exceeds about 70 cm H_2O. Even though a fully closed APL valve can sustain a pressure of 70 cm H_2O, the peak pressure developed in the above scenario plateaus at 40 – 50 cm H_2O because of the compliance characteristics of the breathing bag. For some time, the breathing bag keeps on increasing in size with minimal change in pressure once the pressure is at 40 - 50 cm H_2O.

Learning objectives:

1. The compliance curve of a breathing bag limits the pressure rise in the circuit to 40 – 50 cm H_2O.
2. The maximum sustainable pressure with a fully closed APL valve is generally about 70 cm H_2O.
3. An APL valve is a pressure-threshold device in most contemporary anesthesia machines, and a variable flow resistance device in others such as older Dräger Narkomeds.

Question 2 – Manual ventilation. During manual ventilation, when does excess gas exit the breathing circuit and enter the scavenging system?

Answer: During inspiration

Demonstration using [VAM simulation] (coordinates refer to [VAM grid map]):

a. Press “Reset “ (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag the O_2 flowmeter control knob icon (C-7) counterclockwise until the bobbin is halfway up the tube
c. Click on the selector knob icon (G-4) to select manual ventilation.
d. Wait until the breathing bag is full or press the O_2 flush icon (D-6) to fill the bag
e. Click on the breathing bag icon (I-3) to squeeze the bag and deliver a manual breath. *A portion of the gas molecules in the bag exit the APL valve and enter the scavenging system during inspiration. The other portion of gas leaving the bag flows through the CO_2 absorber on its way to inflating the patient’s lungs.*

Explanation: An APL valve is a pressure threshold device or a variable orifice (flow resistance) device. The APL valve (G-5) in the Virtual Anesthesia Machine simulation is a pressure-threshold device. The maximum pressure is generated when the bag is initially squeezed. If the pressure exceeds the pressure threshold at which the APL valve is set, gas will exit through the APL valve during inspiration. Gas will also exit via the APL valve with a variable flow resistance APL valve that is open.

Learning objectives:

1. In manual ventilation, excess gas leaves the circuit during inspiration.

Post-test questions – Manual ventilation

1. Is the APL valve on contemporary anesthesia machines a variable-orifice device or a pressure threshold device?

2. What is the sustainable airway pressure when a pressure-threshold APL valve is set to wide open?

3. What is the maximum pressure sustained by a completely closed pressure-threshold APL valve?

4. Are the gases exhaled by the patient scrubbed of CO_2 before entering the breathing bag during manual ventilation?

5. What is the compliance curve for a breathing bag complying with ANSI standards?

e. List of mechanical ventilation learning objectives

1. What is the exit for gas during the inspiratory phase of mechanical ventilation?

2. Why you should not flush during mechanical inspiration

3. What is the largest consumer of O_2 during mechanical ventilation with a FGF of 3.5 L/min N_2O, 1.5 L/min O_2, set VT 1,000 ml and RR 12 bpm?

Question 1 – Mechanical ventilation. What is the exit for gas during the inspiratory phase of mechanical ventilation?

Answer: There is none. Trick question.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag the O_2 flowmeter control knob icon (C-7) counterclockwise until the bobbin is halfway up the tube
c. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator
d. When the bellows starts to travel down (corresponding to mechanical inspiration), click on the "Pause animation" text (D13, D14, D15) to freeze the animation. *The ventilator relief valve (G-7) is pressurized shut by the drive gas during mechanical inspiration. There is no exit for gas during the time period corresponding to mechanical inspiration.*

Explanation: The ventilator relief valve is the outlet for excess gas during mechanical ventilation but it only relieves gas during exhalation. It is pressurized shut by the drive gas during mechanical inspiration.

Learning objectives:

1. During mechanical ventilation, there is no exit for gas during the time period corresponding to mechanical inspiration. This has clinical consequences if, for example, an O_2 flush is activated during mechanical inspiration.

Question 2 – Mechanical ventilation. Why you should not flush during mechanical inspiration

Answer: Because the O_2 flush gas will flow to the lungs and hyperinflate the lungs until the inspiratory pressure limit (if present) is reached, creating a risk of barotrauma.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator
c. Click on the airway pressure gauge icon (C-2) to enlarge the pressure gauge
d. Click and hold on the O_2 flush valve icon (D-6) to initiate and maintain an O_2 flush during numerous breath cycles. *The lungs become hyperinflated and display a stylized representation of barotrauma. The pressure gauge indicates pressures as high as 55 cm H_2O.*

Explanation: An O_2 flush delivers about 60 L/min (about 1 L/second) into the breathing circuit. The ventilator relief valve is pressurized shut during mechanical inspiration. The default inspiratory pressure limit (L-13) is set at 50 cm H_2O on the VAM simulation. Many actual machines have the inspiratory pressure limit set at higher pressures that may not prevent barotrauma. The ventilator relief valve will only be depressurized when the inspiratory pressure limit is exceeded. Some traditional machines, such as older Narkomeds, did not feature an inspiratory pressure limit and relied on an internal pressure relief valve set at 120 cm H_2O to limit overpressure.

Learning objectives:

1. Do not flush during mechanical inspiration (when the bellows is travelling down)
2. Flush during exhalation (when the bellows is travelling up)
3. If you are not comfortable with timing the O_2 flush, you may elect to turn off the ventilator and then flush. But remember to turn the ventilator back on afterwards!
4. An O_2 flush generates an inflow of O_2 of about 60 L/min (or about 1 L/second) into the breathing circuit.

Question 3 – Mechanical ventilation. During mechanical ventilation of a patient with a FGF of 3 L/min N_2O, 3 L/min O_2 and set ventilatory parameters of VT 1,000 ml and RR 12 bpm, the O_2 pipeline supply fails. The O_2 cylinder pressure gauge is reading empty. You open the E cylinder of O_2 and the cylinder pressure gauge now reads 2,000 psig, indicating that there is 660 L of O_2 present. Will the O_2 cylinder last 220 minutes (660 L divided by 3 L/min) before it is exhausted?

Answer: No. The E-cylinder will last much less than 220 minutes.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator. *Note the O_2 molecules being used as the drive gas for the bellows. Look at the piping in D-9, E-9 and F-9 and the space above the bellows when it travels down).*

Explanation: The drive gas is usually a larger consumer of O_2 compared to the O_2 used in the fresh gas flow. The amount of O_2 consumed by the ventilator as drive gas approximates the set minute volume, in this particular scenario, 12 bpm * 1 L = 12 L/min. Thus, the O_2 consumed by the ventilator is 4 times that used to generate the fresh gas flow. Some Dräger ventilators use ejectors ("venturis") to augment the O_2 drive gas with entrained room air and thus may consume less than the minute ventilation.

Learning objectives:

1. The ventilator is usually the largest consumer of O_2 in an O_2-driven bellows ventilator.
2. To minimize O_2 consumption when an anesthesia machine is being supplied by a finite O_2 source such as an O_2 cylinder, switch to manual ventilation to make the O_2 last longer.

Post-test questions - Mechanical ventilation

1. Why is gas spilled during different ventilation phases in manual and mechanical ventilation?
2. Does FGF continue to enter the breathing circuit during mechanical inspiration?
3. Does the magnitude of the FGF affect the delivered tidal volume?
4. What is the cause of the 3 cm H_2O intrinsic PEEP in an upright bellows ventilator?
5. During mechanical ventilation, when does excess gas leave the breathing circuit and enter the scavenging system?
6. In general, is the drive gas in a gas-driven ventilator scavenged?
7. If the drive gas is scavenged, what could be the potential repercussions on airway pressure?

f. List of scavenging system learning objectives

1. What happens if the scavenging vacuum adjustment valve is fully closed?

2. What are the main factors that determine whether the scavenger positive pressure relief valve opens?

Question 1 – Scavenging system. The scavenging hose is connected to a vacuum source. The scavenging vacuum adjustment is fully closed. Will waste anesthetic gases escape to the room during use? If so, will there be an alarm?

Answer: Yes. No.

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click and drag the O_2 flowmeter control knob icon (C-7) counterclockwise until the O_2 bobbin is about 1/3 up the tube
c. Click and drag the N_2O flowmeter control knob icon (C-8) counterclockwise until the N_2O bobbin is about 2/3 up the tube
d. Click on the vaporizer concentration dial icon (A-6) to turn on the vaporizer
e. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator
f. Click on the scavenging vacuum adjustment valve icon (G-10) three (3) times to close it fully. *The scavenging bag (J-9) starts to fill. After the scavenging bag is distended, the scavenging positive pressure relief valve (top leaflet on H-10) on the scavenging manifold lifts up and relieves anesthetic gases containing, among others, N_2O and volatile anesthetics into the room.*

Explanation: Adjustment of the scavenging vacuum adjustment valve (SVAV) sets the gas flow that can be suctioned. When the SVAV is fully closed, there is no suction applied to the scavenging manifold to draw away anesthetic gases directed into the scavenging manifold. Thus, a net accumulation of gas in the scavenging manifold results. Initially, the accumulation of gas is absorbed by the scavenging bag which functions as buffer. Once the scavenging bag fills up, pressure begins to rise in the scavenging manifold. Without a positive pressure relief valve, pressure would build up in the scavenging manifold and eventually be transmitted to the breathing circuit and the patient's lungs. When pressure in the scavenging manifold increases past the threshold of the positive pressure relief valve, the valve leaflet lifts up to prevent pressure build-up in the scavenging manifold.

Learning objectives:

1. The scavenging adjustment valve must be properly adjusted such that the bag is not over-distended, an indication that anesthetic gases are being spilled into the room
2. There is no alarm to warn of spillage of anesthetic gases in the room

Question 2 – Scavenging system. What are the main factors that determine whether the scavenging positive pressure relief valve opens?

Answer: The scavenging vacuum adjustment valve setting, the central vacuum level, the total FGF, and the degree of inflation of the scavenging bag

Demonstration using VAM simulation (coordinates refer to VAM grid map):

a. Press "Reset " (E-13) to start simulation afresh, without carry-over from previous interventions
b. Click on the ventilator on/off switch icon (F-9) to turn on the ventilator. *At the minimal FGF of 300 ml/min O_2, the outflow from the scavenging system exceeds the inflow. The negative pressure relief valve (bottom leaflet in H-10) lifts up to break the vacuum and entrain room air.*
c. Click and drag the O_2 flowmeter control knob icon (C-7) counterclockwise until the bobbin is at the maximum setting to increase FGF. *The negative pressure relief valve reseats itself after a few breaths because the inflow is now matched to the FGF.*
d. Click and hold on the O_2 flush valve icon (D-6) during exhalation to increase inflow into the scavenging manifold. *The positive pressure relief valve lifts up because inflow exceeds outflow.*
e. Click on the scavenging hose connector icon (H-12) to disconnect the scavenging hose and simulate a change in the central vacuum level. *The positive pressure relief valve lifts up because inflow exceeds outflow.*
f. Click on the scavenging hose connector icon (H-12) to reconnect the scavenging hose. *The positive pressure relief valve reseats itself.*

Explanation: An active scavenging system like the one simulated in the Virtual Anesthesia Machine operates by balancing the inflow into, and outflow from the scavenging manifold. The scavenging bag acts a buffer and can temporarily absorb transient surges in gas inflow (resulting for example from a brief O_2 flush). If the average inflow exceeds the average outflow, the buffering capacity of the scavenging bag will be eventually overwhelmed and the positive pressure relief valve will silently spill anesthetic gases into the room. Closing the SVAV will reduce the outflow. A drop of the central vacuum level without modification of the SVAV setting will result in a reduction of outflow. An increase in FGF or an O_2 flush will increase inflow. The SVAV provides a means to re-adjust the balance in the scavenging manifold when inflow/outflow conditions change.

Learning objectives:

1. The scavenging vacuum adjustment valve (SVAV) must be re-adjusted when FGF changes
2. Turn the SVAV counter-clockwise to increase suction when FGF increases or if the scavenging bag appears over-distended until the scavenging bag is not over-distended and cycles with each breath

Post-test questions – Scavenging system

1. What happens if the scavenging vacuum adjustment valve is fully open?
2. What are the main factors that determine whether the vacuum (negative pressure) relief valve opens?
3. What are the main factors determining the volume of gas in the scavenging bag?
4. What is the function of the scavenging system vacuum (negative pressure) relief valve?
5. What is the function of the scavenging bag?
6. What is the function of the scavenging system positive pressure relief valve?
7. Is an alarm generated if the scavenging system is spilling anesthetics into the OR?