

Ventilators are commonly used in the operating room and in the ICU to deliver mechanical ventilation to the lungs. Breath control complexity gives rise to the need to identify and describe "modes" of ventilation. Assist Lec.: Athra'a Sabeeh 2nd Semester 2023–2024 12 Multi-compartment model of the respiratory system connected to a ventilator using electronic analogs 2nd Semester 2023–2024 13 Assist Lec.: Athra'a Sabeeh 14 Assist Lec.: Athra'a Sabeeh 2nd Semester 2023–2024 Modern ventilator machines have two separate but inter connected systems; a pneumatic flow system and an electronic control system.

The pneumatic flow system enables the flow of gas through the ventilator. The gases (oxygen and medical grade air) enter the air / oxygen mixer which they combine at the required percentage. The gases then enter a large reservoir tank to be compressed. An electronically controlled flow valve proportion the gas flow from the reservoir tank to the patient's breathing circuit.

In some ventilators, an air compressor is used in place of a compressed air tank. Ventilators require electric power, oxygen, and compressed air usually supplied via external power source as well as via hospital's central gas supply (with supply pressure of approximately 3–6 bar). In areas without central gas supply or during transportation of patients within the hospital, it is necessary to ensure the functioning of the device by other means. Potential solutions include the use of separate compressors, compressed gas cylinder packs, and accumulators. Ventilator Functional Block Diagram

Gas mixer allows the user to vary the oxygen concentration of inspiratory gas between 21% and 100% by volume: a. Mechanical gas mixers (old technology). b. Electronically-controlled gas mixer integrated in ventilator (standard now). Gas mixers usually responsible for ensuring that breathing gas to be supplied is prepared and delivered in required quantity and rate. It is often the threshold ranges which pose the greatest challenges to these metering systems. For volume of 20 ml with an oxygen concentration of 30% by volume, 17.7 ml of gas must be delivered via a compressed air valve and 2.3 ml via an oxygen valve. The pressure or flow generator is responsible for delivering mixed gas prepared by the gas mixer according to selected ventilation parameters. Flow generator is a controlled valve whose output provides defined gas flow with output pressure is not specified. Pressure generator behaves similar to compressor, whose output provides defined pressure with unspecified gas flow. It's often used to drive ventilators not dependent on compressed air that use ambient air for ventilation. 2nd Semester 2023–2024 Assist Lec.: Athra'a Sabeeh 15 Breathing System Breathing system forms interface between patient and the ventilator. Clinical ventilators are usually connected to patient via inspiratory and expiratory hose (dual-hose circuit). Expiratory valve is closed during the inspiratory phase where gas flow delivered through inspiratory port passes through breathing gas humidifier before entering patient's lungs to make it adapted to climatic conditions in patient's lungs. After inspiratory phase, patient exhales when expiratory valve is opened, expiratory gas passes through ventilator again, but not reused for following inspiration. Based on this characteristic, the breathing systems of ventilators are also referred to as non rebreathing circuits. Gas Humidifier Humidifiers are used to warm and humidify inspiratory gas. Dry and relatively cool supply gas would dry out the patient's airways with risk of causing irreversible damage to the ciliated epithelium. Active gas humidifiers are located in the inspiratory limb and use electrical energy to heat a water bath. When the cold, dry gas passes over the water surface it

absorbs water molecules and is thus warmed and humidified. Example: Pass-over humidifiers and Bubble-through humidifiers. Passive breathing gas humidifiers, termed heat and moisture exchangers (HMEs), are placed close to patient and designed to buffer significant fraction of moisture and heat expired by patient. Retained moisture is then used to condition inspired gas passing through HME during next inspiration. 2nd Semester 2023–2024 Assist Lec.: Athra'a Sabeeh 16 17 Assist Lec.: Athra'a Sabeeh 2nd Semester 2023–2024 Expiratory (Exhalation) Valve Expiratory valve switches between inspiration and expiration phases of Ventilation. If valve is not opened completely during expiration, positive end-expiratory pressure (PEEP) is created in lungs. PEEP is therapeutically important as it increases gas exchange surface of lungs. Adequate PEEP can also prevent collapse of individual alveolar areas. If expiratory valve is controlled during inspiratory phase, it can compensate for undesired pressure rises in breathing system caused, for example, by patient coughing. 2nd Semester 2023–2024 Assist Lec.: Athra'a Sabeeh 18 19 Assist Lec.: Athra'a Sabeeh 2nd Semester 2023–2024

Operating and Display Unit

Operating and display unit is the interface between ventilator and user. Often touch screens designed to display pressure and flow curves as well as multiple menus for setting different ventilation modes, adjusting alarm limits or measured value overviews, etc. Parameters settings entered in operating unit control device components and therefore determine ventilation pattern applied to the patient. Alarm System and Patient Monitor Ensure that ventilation parameters set in operating and display unit are actually applied. This system issues audible and visual alarms to alert staff to critical changes in the patient's condition or technical malfunctions monitor the following:

1. Inspiratory oxygen concentration (controlled by the gas mixer)
2. Ventilation Pressure and Volume (to monitor the pressure/flow generator)
3. Inspiratory breathing gas temperature (when using active gas humidifier)

Patient monitoring is used to monitor the patient's vital functions

1. Electrocardiogram (ECG)
2. Blood pressure (noninvasive and/or invasive)
3. Oxygen saturation
4. Carbon dioxide concentration in the breathing gas

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Modern ventilator machines consist of two separate but inter-connected systems: the pneumatic flow system and an electronic control system.

The pneumatic flow system enables the flow of gas through the ventilator. Oxygen and medical grade air enter the ventilator at 3.5 bar (50 psi) pressure through built-in 0.1 micron filters. The normal operating range is 2 to 6 bar or 28 to 86 psi. These gases enter the air/oxygen mixer where they combine at the required percentage and reduced in pressure to 350 cmH₂O. The gases then enter a larger reservoir tank which holds about 8 liters of mixed gases, when compressed to 350 cmH₂O. An electronically controlled flow valve proportionates the gas flow from the reservoir tank to the patient breathing circuit. In some ventilators, an air compressor is used in place of a compressed air tank. The primary objective of the device is to ensure proper level of oxygen in the inspiratory air and deliver tidal volume according to the clinical requirements. As the gases leave the ventilator, they pass by an oxygen analyzer, a safety ambient air inlet valve and a back-up mechanical overpressure valve. The ambient valve provides the patient the ability to breathe room air when the ventilator fails or the pressure in the patient circuit drops below -10 cm of H₂O. In the patient breathing circuit is a bidirectional flow sensor to measure the gas flows. The exhaled gases exit through an electronically controlled

exhalation valve located at the ventilator. With the introduction of microprocessors for control of metering devices, electromechanical valves have gained popularity. The microprocessor controls each valve to deliver the desired inspiratory air and oxygen flows for mandatory and spontaneous ventilation. A high pressure valve is used to provide safety in case the pressure in the patient circuit exceeds 110 cmH₂O. Types of Ventilators

Modern Ventilators (Microprocessor controlled) The electronic control system may use one or more microprocessors and software to perform monitoring and control functions in a ventilator. These parameters include setting of the respiration rate, flow waveform, tidal volume, and oxygen concentration of the delivered breath, peak flow and PEEP. The PEEP selected in the mandatory mode is only used for control of exhalation flow. The microprocessor utilizes the above parameters to compute the desired inspiratory flow trajectory. The system consists of monitors for pressure flow and oxygen fraction. The sensors are connected to electronic processing circuits which makes them available for digital readouts.

The signals are also compared with pre-set alarm levels so that if they fall outside a pre-determined normal range, alarms are sounded. The pressure sensors are normally of semiconductor strain gauge type placed in a bridge configuration. For measurement of fraction of oxygen in the inspired air, a fuel cell type oxygen sensor is used. This sensor generates a current proportional to O_2 .

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A new technique for ventilating patients at frequencies much higher than the respiration rate has recently been introduced. This method has been shown to improve CO_2 washout and provide adequate oxygenation without the requirement for high inspiratory pressures. The key principle in this technique is to provide tidal volumes equal to or smaller than the deadspace, at very high rates. In conventional positive pressure ventilation, CO_2 elimination is directly controlled by the amount of applied minute ventilation. However, it is known that mean airway pressure is the parameter that best correlates with improvement in oxygenation. Gas transport during conventional ventilation is attributed to two basic mechanisms: (i) convection or flow of gas through the conducting airways, and (ii) molecular diffusion of gases into the alveoli and pulmonary capillaries. The tidal volume (V_T) applied to the patient at the Y-piece can be divided into the volume used to ventilate the deadspace (V_D) and the alveolar volume ($V_{T_{alv}}$). Only the alveolar volume takes part in the gas exchange process. Therefore, High Frequency Ventilators

$$V_{T_{alv}} = V_T - V_D$$

The portion of the tidal volume used to ventilate the deadspace does not take part in capillary gas exchange and is therefore wasted. To overcome the problem of wasted ventilation in conventional ventilation, the inspiratory pressure is increased in order to increase the total tidal volume. Unfortunately, however, this also increases the mechanical stress on the lung and has been associated with various traumas. High frequency ventilation has been shown to provide adequate alveolar ventilation and oxygenation without the requirement for high inspiratory pressures. The ventilator generates high frequency rate from 5 to 20 Hz (300 to 1200 pulse/minute). Although several methods are available to generate the high frequency pressure waves, the Babylog 8000 makes use of an oscillating diaphragm mechanism. This mechanism is computer-controlled and can precisely determine the shape of the pressure swings. An alternative method of achieving HF ventilation is based on the jet principle in which a small diameter tube is passed down a tracheal cannula and is either terminated at its distal end or extended into the trachea itself. Short pulses of higher pressure oxygen are introduced into the airway through the cannula at frequencies well above the normal

respiration rate. This technique has the disadvantage of forcing volume into the patient and then leaving the patient to exhale passively, which may lead to some trapped volume inside the lung increasing the mean lung pressure. This problem is overcome by ensuring that the pressure during the exhalation phase is negative with respect to the set PEEP. 24 Assist Lec.: Athra'a Sabeeh 2nd Semester 2023–2024

The main task of a humidifier is to replace humidity in the upper air passages which has been lost by intubation. The humidity should be as close to 100% as possible, or speaking in terms of water, the absolute content per liter of breathing gas should be more than 30 mg, regardless of environmental conditions. Therefore, in order to prevent damage to the patient's lungs, the air or oxygen applied during respiratory therapy must be humidified. Thus, all ventilators include arrangements to humidify the air, either by heat vaporization (stream) or by bubbling an air stream through a jar of water. When water or some type of medication is suspended in the inspired air as an aerosol it is to be administered to the patient, a device called a nebulizer is used. In this device, the water or medication is picked up by a high velocity jet of air/oxygen and made to impact against one or more baffles to break the substance into controlled-sized droplets which are then applied to the patient via a respirator. More effective and efficient nebulizers are based on the use of high intensity ultrasound energy which vibrates the substance (water or medication) to produce a high volume of minute particles. Ultrasonic nebulizers do not depend upon breathing gas for operation and thus therapeutic agents can be conveniently administered during ventilation procedure. Aspirators are often included as part of a ventilator to remove mucus and other fluids from the airways. Alternatively, a separate suction device may be utilized to achieve the same purpose.

Humidifiers, Nebulizers and Aspirators 1. Breathing pattern I. Volume Control (VC) A ventilator can be classified as either a pressure, volume, or flow controller. When classifying modes of ventilation, we do not need to be so specific. Because control of volume implies control of flow and vice versa, we can refer to two basic modes of ventilation: volume control and pressure control. II. Pressure Control (PC) Pressure control means that the airway pressure waveform is preset (for example by setting peak inspiratory pressure and end expiratory pressure). Tidal volume and inspiratory flow are then dependent on these settings and the elastance and resistance of the respiratory system. Dual Control (DC) There are clinical advantages and disadvantages to volume and pressure control. Simply put, volume control results in a more stable minute ventilation (and hence more stable gas exchange) than pressure control if lung mechanics are unstable. On the other hand, pressure control allows better synchronization with the patient because inspiratory volume and flow are not limited to arbitrary preset values. While it is possible to control only one variable at a time, a ventilator can automatically switch between pressure control and volume control in an attempt to guarantee minute ventilation while maximizing patient synchrony. 25 Assist Lec.: Athra'a Sabeeh 2nd Semester 2023–2024 Modes of

Ventilation A. Primary breath control variable 26 Assist Lec.: Athra'a Sabeeh 2nd Semester 2023–2024

There are two types of dual control. Dual control between breaths means that the ventilator controls pressure during each breath but adjusts the pressure limit to achieve a tidal volume target over several breaths.

Alternatively, the ventilator can switch between volume and pressure control during a single breath (dual control within breaths, figure below). Modes of Ventilation 1. Breathing pattern B. Breath sequence The second component of the breathing pattern specification is the breath sequence. A breath is defined as a positive change in airway flow (inspiration) paired with a negative change in airway flow (expiration),

both relative to baseline flow and associated with ventilation of the lungs. But the definition allows the superimposition of, say, a spontaneous breath on a mandatory breath or vice versa. On the other hand, mandatory breaths are superimposed on spontaneous breaths during high-frequency oscillatory ventilation.

The classification of modes requires the definition of two basic types of breaths: spontaneous and mandatory. A spontaneous breath is a breath for which the patient controls the start time and the tidal volume. That is, the patient both triggers (starts) and cycles (ends) the breath. A spontaneous breath may either be assisted or unassisted. A mandatory breath is a breath for which the machine sets the start time and/or the tidal volume. That is, the machine triggers and/or cycles the breath. 2nd Semester 2023–2024 27 Assist Lec.: Athra'a Sabeeh there are three possible sequences of breaths, designated as follows: I. Continuous Mandatory Ventilation (CMV): all breaths are mandatory II.

Continuous Spontaneous Ventilation (CSV): all breaths are spontaneous III. Intermittent Mandatory Ventilation (IMV): breaths can be either mandatory or spontaneous. Breathes can occur separately or breaths can be superimposed on each other. When the mandatory breath is patient-triggered, it is commonly referred to as synchronized IMV (SIMV). However, because the trigger variable can be specified in the description of phase variables, we will use IMV instead of SIMV to designate general breath sequences. When we add the breath sequence to the control variable in classifying a mode, we get a greater ability to discriminate modes. We can distinguish between, say, pressure controlled IMV and pressure controlled CSV. If we confine ourselves to classifying modes based solely on the breathing pattern, we see that there are only eight possibilities: VC–CMV, VC–IMV, PC–CMV, PC–IMV, PC–CSV, DC–CMV, DC–IMV, and DC–CSV. Note that VC–CSV is impossible by definition.

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We have discussed "control variables" and the differences between pressure, volume, and dual control but, we have not really explained what is meant by "control" in the first place. There are two general ways to control a variable; open loop control and closed loop control. The vast majority of ventilators used in the world provide "conventional" ventilation. This employs breathing patterns that approximate those produced by a normal spontaneously breathing person. 2nd Semester 2023–2024 6 Assist Lec.: Athra'a Sabeeh 7 Assist Lec.:

Athra'a Sabeeh 2nd Semester 2023–2024 Automating Ventilator Lung Volume and Capacity Volumes: There are four volumes: (1) tidal volume (V_t) is the volume of gas inhaled or exhaled during each respiratory cycle. (2) inspiratory reserve volume (IRV) is the maximal volume of gas inspired from end–inspiration. (3) expiratory reserve volume (ERV) is the maximal volume of gas exhaled from end–expiration. (4) residual volume (RV) is the volume of gas remaining in the lungs following a maximal exhalation.

Capacities: There are four capacities, each of which contains two or more primary volumes: (1) total lung capacity (TLC) is the amount of gas contained in the lung at maximal inspiration. (2) vital capacity (VC) is the maximal volume of gas that can be expelled from the lungs by a forceful effort following maximal inspiration, without regard for the time involved. (3) inspiratory capacity (IC) is the maximal volume of gas that can be inspired from the resting expiratory level. (4) functional residual capacity (FRC) is the volume of gas in the lungs at resting end–expiration. Tidal volumes are large enough to clear the anatomical dead space during inspiration and the breathing rates are in the range of normal rates. Gas

transport in the airways is dominated by convective flow and mixing in the alveoli occurs by molecular diffusion. There is also a class of "high frequency ventilator" that delivers tidal volumes less than dead space volume at frequencies up to 15 Hz. High frequency ventilators, in theory, minimize the risk of damage to diseased lung tissue that could be caused by volumetric over distention with normal tidal volumes.

Control Type	Description	Example	Control Scheme	Example Mode	Example Ventilator	Setpoint
Output matches fixed input	Tidal volume or peak pressure held constant by adjusting control variable	Pressure control Assist control	Pressure support	Siemens Servo	Hamilton Galileo PB840	Servo
Output matches dynamic input	Pressure made proportional to volume and/or flow	Proportional Assist Automatic Tube Compensation	Not available in US	Drager Evita4	Setpoint Dual Control	
Automatic switch between pressure and volume control to maintain operator defined setpoint	Volume control overrides pressure control with breath if set tidal volume not met	Pressure Limited Ventilation	Volume Assured Pressure Support	Drager Evita4	Bird 8400 ST	Adaptive Dual Control
Automatic adjustment of pressure setpoint to maintain an operator selected volume setpoint	Pressure limit adjusted to maintain set tidal volume, using lung mechanics	Pressure Regulated Volume control	AutoFlow	Siemens Servo 300	Drager Evita4	Optimal Dual Control
Automatic adjustment of both pressure and volume setpoint to minimize other variables	Pressure limit and tidal volume adjusted to minimize work of breathing, using lung mechanics	Adaptive Support Ventilation	Hamilton Galileo 32	Assist	Lec.: Athra'a Sabeeh	2nd Semester

2023–2024 A. The phase variable is a signal that is measured and used by the ventilator to initiate some part, or phase, of the breath cycle. The variable causing a breath to begin is the trigger variable. A variable whose magnitude is constrained to some maximum value during inspiration is called a limit variable. The variable causing a breath to end is the cycle variable. During expiration, the ventilator usually maintains some level of pressure at or above atmospheric pressure, which is referred to as the baseline variable. Thus, to understand ventilators we must first understand their four mechanical characteristics: 1) Input power 2) Power conversion and transmission 3) Control system 4) Output (pressure, volume, and flow waveforms) The physical model (Pneumatic model) of breathing mechanics most commonly used is a rigid flow conducting tube connected to an elastic compartment. The simplest mechanical device we could advise to assist a person's breathing would be a hand-driven, syringe-type pump that is fitted to the person's mouth and nose using a mask. A variation of this is the self-inflating, elastic resuscitation bag. Open loop control is essentially no control.