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Great Ormond Street

Hospital for Children

NHS Trust

Principles of Ventilation

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Updated by Simona Lampariello, May 2007, Shruti Agrawal Dec 08

Associated clinical guidelines/protocols:

- Ventilator user guides on intranet
- Guideline

Fundamental Knowledge:

List of topics relevant to PIC are covered in membership examinations, will not be repeated

- Storage of oxygen, NO, Helium, compressed air.

Information for Year 1 ITU Training (basic):

Year 1 ITU curriculum

Ventilation:

- Indications for mechanical ventilation
- Principles of ventilation: Flow, volume & pressure relationships
- Cardiopulmonary interactions in IPPV
- Basic methods of ventilatory support: non-invasive ventilation (face mask IPPV & CPAP) and invasive, positive pressure ventilation using CMV (volume and pressure) and HFOV. Mention assist modes, trigger modes to a basic level.
- Lung protective ventilation strategies –permissive hypercarbia, low tidal volume, improve V/Q mismatch
- Detection and management of complications of mechanical ventilation – volutrauma
- Principles of weaning from mechanical ventilation

Investigations:

- Interpretation of blood gas
- Interpretation of chest x-rays; collapse, consolidation, infiltrates (including ALI/ARDS), pneumothorax, pleural effusion, pericardial effusion, position of cannulae, tubes or foreign bodies, airway compression, cardiac silhouette, mediastinal masses

Curriculum Notes for Year 1: Indications for mechanical ventilation

- 1) Oxygenation abnormalities
 - a) Cyanosis with $Fi O_2 \geq 0.6$
 - b) $PaO_2 < 7 \text{ kPa}$ with $Fi O_2 > 0.6$
 - c) $\text{Alveolar-arterial oxygen gradient} = P(A-a) O_2 > 450 \text{ mm Hg}$ with $Fi O_2 1.0$
 - d) Shunt fraction $> 15\text{-}20\%$
 - e) Others

- a. Need for PEEP/Failure to non-invasively oxygenate
- b. Excessive work of breathing with \approx normal range ventilation

2) Ventilation abnormalities

- a. Apnoea
- b. GCS < 8 (also for airway protection)
- c. Increased airway resistance/obstruction with $\text{PaCO}_2 \uparrow$ and acidosis
- d. *Decreased ventilatory drive with $\text{PaCO}_2 >$ or rising PaCO_2*
- e. Neuromuscular diseases e.g. Guillan-Barré
 - FEV < 15 ml/kg and -ve inspiratory pressure < -20 cm H₂O
- f. Respiratory muscle dysfunction
 - i. Respiratory muscle fatigue
 - ii. Chest wall abnormalities (eg flail chest)
 → inadequate ventilation + dead space/TV ratio > 0.6

3) Others

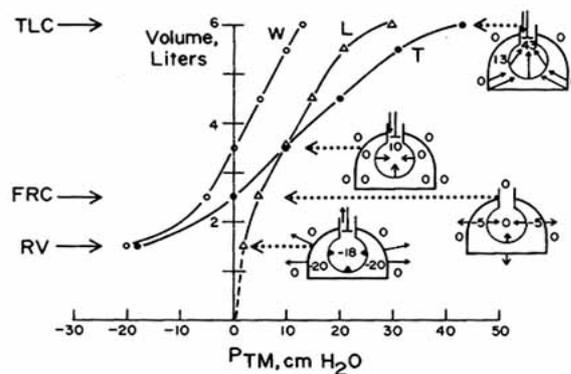
- a. Permit sedation or neuromuscular blockade-see 4
- b. Decrease systemic + myocardial O₂ consumption
- c. Reduce intracranial pressure: see Mx head injury
- d. To prevent atelectasis
- e. Post arrest

4) Surgical indications –(haemostasis/anastomotic integrity)

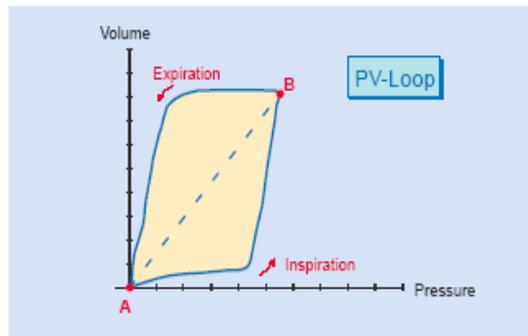
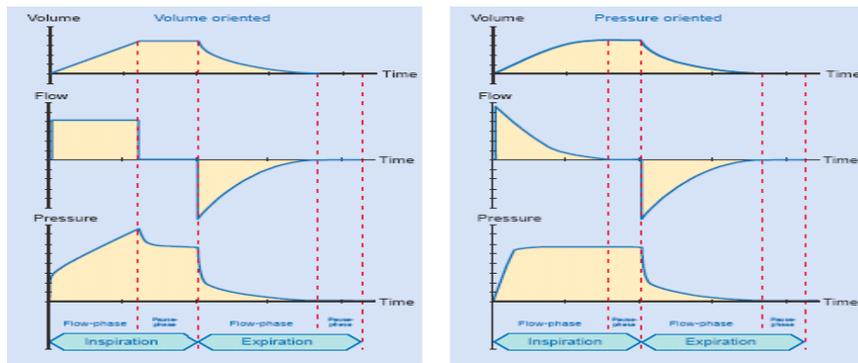
- a. Airway reconstruction
- b. Gastric transposition
- c. Post-spinal fusion

Principles of ventilation

- **Flow, volume & pressure relationships**



(http://physioweb.med.uvm.edu/pulmonary_physiology/)



(http://www.draeger.com/MT/internet/pdf/CareAreas/CriticalCare/cc_loops_book_en.pdf)

All wonderfully explained in attached basic review article (*Pulmonary and renal pressure-flow relationships: what should be taught?* Goodman *Advan. Physiol Edu* 25:15-28,2001;1043-6 AND in 'Draeger loops booklet' –attached)

Basic methods of ventilatory support:

1) Non-invasive



Advantages: Avoids intubation e.g. conditions with high intubation mortality ie immunodeficiency /oncology, asthma (Ferrer et al. Noninvasive ventilation in severe hypoxemic respiratory failure: a randomized clinical trial. *Am J Respir Crit Care Med* 2003;168:1438–44)

Avoid re-intubation- (NB Esteban et al. Noninvasive PPV for Respiratory Failure after Extubation. *N Engl J Med* 2004; 350:2452-60, 2004)

a) Children

Face mask/ nasal masks:

Sullivan CPAP/IPPV <http://resmed.com.au/> data, Evita 4 **BiPAP/APRV**

Helmet ventilation:



(Ref: Rocco et al. Noninvasive ventilation by Helmet or facemask in immunocompromised patients. Chest 2004; 126: 1508-15.)

Advantages: Better tolerated in children phobic to the mask and straps, and also those with difficulties in fitting the mask.

Disadvantages: Misting, difficulty with mouth cares. ? carbon dioxide rebreathing.

b) Neonates

EME CPAP, nasal prong/ mask CPAP

(Ref: Cochrane Database Syst Rev. 2008; 1: CD00297)

Heliox

Helium - colourless, odourless, inert gas with no direct pharmacological or biological effects, no intrinsic bronchodilatory or anti-inflammatory properties. Density of helium is 1/7 that of air. Carbon dioxide diffuses through helium four to five times faster than through air. Heliox is a helium-oxygen mix. By its lower density, heliox improves gas flow through high-resistance airways, by changing turbulent flow into a more laminar flow type with improved diffusion characteristics.

Also, with a lower gas density, helium provides a higher flow rate even if it remains turbulent. Thus, with its lower density, helium as a "carrier gas" results in a lower resistance to gas flow allowing for increased bulk flow, increased oxygen flow, and decreased work of breathing. Heliox has shown to prevent intubation in asthma when started early (bridge until steroids kick in) and to improve delivery of inhaled bronchodilators. In bronchiolitis, where it has shown to reduce LOS, it may also prevent intubation. In post-extubation stridor it may prevent re-intubation.

(Ref: Heliox administration in the pediatric intensive care unit: An evidence-based review Vineet K. Pediatr Crit Care Med 2005;6:204–211, Use of Heliox in children. Myers TR. Resp Care 2006; 51: 632-9.)

2) Invasive

- Can manipulate
 - Minute Ventilation - \uparrow respiratory rate, tidal volume)
 - Pressure Gradient = A-a equation (\uparrow atmospheric pressure, FiO_2 , increase ventilation, change RQ)
 - Surface Area = volume of lungs available for ventilation (\uparrow volume by \uparrow airway pressure, i.e. mean airway pressure)
 - Solubility = ? perfluorocarbons?

Ventilators deliver gas to the lungs using positive pressure at a certain *rate*. Amount of gas delivered can be *limited* by time, pressure or volume. Duration can be *cycled* by time, pressure or flow.

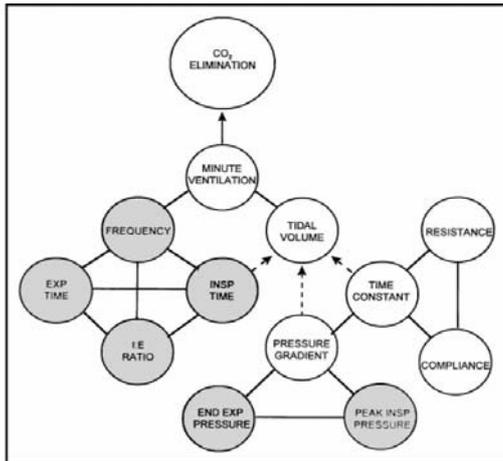


FIGURE 1. Relationships among various ventilator-controlled (shaded circles) and pulmonary mechanics (unshaded circles) that determine minute ventilation during pressure-limited, time-cycled ventilation. The relationships between the circles joined by solid lines are described by simple mathematical equations. The dashed lines represent relationships that cannot be calculated precisely without considering other variables, such as pulmonary mechanics. Thus, simple mathematical equations determine the time constant of the lungs, the pressure gradient, and the inspiratory time. These, in turn, determine the delivered tidal volume, which when multiplied by the respiratory frequency, gives the minute ventilation. Alveolar ventilation can be calculated from the product of tidal volume and frequency when dead space is subtracted from the former. From Carlo WA, Greenough A, Chatburn RL. *Advances in conventional mechanical ventilation*. In: Boynton BR, Carlo WA, Jobe AH, eds. *New Therapies for Neonatal Respiratory Failure*. Boston, Mass: Cambridge University Press; 1994.

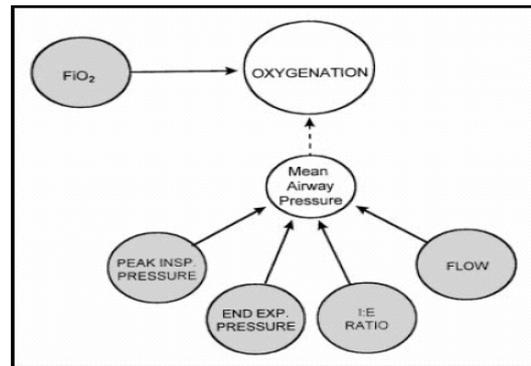


FIGURE 2. Determinants of oxygenation during pressure-limited, time-cycled ventilation. Shaded circles represent ventilator-controlled variables. Solid lines represent the simple mathematical relationships that determine mean airway pressure and oxygenation, and dashed lines represent relationships that cannot be quantified with a simple mathematical method. From Carlo WA, Greenough A, Chatburn RL. *Advances in conventional mechanical ventilation*. In: Boynton BR, Carlo WA, Jobe AH, eds. *New Therapies for Neonatal Respiratory Failure*. Boston, Mass: Cambridge University Press; 1994.

Nomenclature

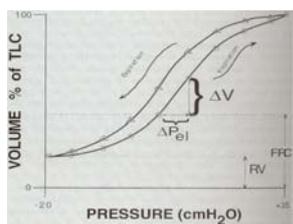
- CPAP: continuous positive pressure ventilation
- FiO_2 : fraction of inspired oxygen concentration
- I;E: inspiratory to expiratory time
- MAP: mean airway pressure
- PEEP: Positive end expiratory pressure
- PIP: Peak inspiratory pressure
- RDS: respiratory distress syndrome
- T_E : expiratory time, T_I : inspiratory time
- CMV: Conventional mechanical ventilation
- Pressure above PEEP (PAP or ΔP)
- Tidal Volume: amount of gas delivered with each breath

Modes:

- Control Modes:
 - every breath is fully supported by ventilator
 - in classic control modes, patients *unable* to breathe except at the controlled set rate
 - in newer control modes, machines may act in assist-control, with a minimum set rate and all triggered breaths above that rate also fully supported.
- IMV Modes: intermittent mandatory ventilation modes - breaths “above” set rate not supported
- SIMV: vent synchronizes IMV “breath” with patient’s effort
- Pressure Support: vent supplies pressure support but no set rate; PS can be fixed or variable (volume support, volume assured support etc)
- Whenever a breath supported by ventilator, regardless of mode, the limit of support determined by preset pressure *OR* volume.
 - Volume Limited: preset tidal volume
 - Pressure Limited: preset PIP or PAP

If volume is set, pressure varies, if pressure is set, volume varies, according to compliance.

COMPLIANCE = Δ Volume / Δ Pressure



(Ref: Burton SL & Hubmayr RD: Determinants of Patient-ventilator Interactions: Bedside Waveform Analysis, in Tobin MJ (ed): *Principles & Practice of Intensive Care Monitoring*)

High Frequency Oscillation (HFOV)



(Courtesy: sensormedics website)

Provides small tidal volumes (really an Amplitude referred to as Delta P) usually equal to, or less than, the dead space; 150 millilitres, at very fast rate (Hertz-Hz) of between 4-5 breaths per second. Enables maintenance of minute volume. Lungs kept open to constant airway pressure via mean pressure adjust system (ideal 'lung-protective ventilation'). Further, HFOV allows for the decoupling of oxygenation from ventilation allows separate adjustment of either oxygenation or ventilation.

Core is a piston assembly incorporating an electronic control circuit, or square-wave driver powering a linear drive motor consisting of an electrical coil within a magnet (cf permanent magnet speaker). When positive polarity applied to square-wave driver coil is driven forward. Coil attached to rubber bellows (or diaphragm) to create piston. When coil moves forward piston moves toward patient airway creating inspiratory phase and vice versa

- **Amplitude** -means by which TVs delivered (greater amplitude-more volume). Piston displacement → oscillations. Extent amplitude increases depends on resistance to piston eg low compliance- greater pressure in inspiratory phase. Since tidal volumes so low, gas transport mechanisms other than conventional bulk flow must be invoked to explain gas and CO₂ flow (see gas transport....)
- **Mean Pressure Adjust (Paw)**. Mushroom shaped control valve on end of expiratory limb-allows manipulation of Paw enables lung recruitment, keeps lungs and alveoli open at consent pressure avoiding lung expansion/collapse.
- Oscillator speed set by manipulating **frequency**. Breaths/min in Hertz (Hz). 1 Hz equal to one breath/sec i.e.60 breaths/min. 5 Hz gives 5 breaths/sec= 300 breaths /min. NB as frequency increased piston excursion ltd by time allocated each breath

Gas transport under non-physiologic conditions

- o Bulk flow can still provide conventional gas delivery to proximal alveoli with low regional dead space volumes
- o Coaxial flow. Gas in the centre flows inward, gas on the periphery flows outward. Can develop because of the asymmetric low profile of high velocity gases
- o Taylor dispersion produces mixing fresh + residual gas along front of flow of gas through tube.
- o Pendelluft can mix gases between lung regions having different impedances.
- o Augmented molecular diffusion can occur at alveolar level secondary to added kinetic energy from oscillations

Ref:

1. Siau C, Stewart TE. Current role of high frequency oscillatory ventilation and airway pressure release ventilation in acute lung injury and ARDS. Clin Chest Med 2008; 29: 265-75.
2. High-frequency ventilation in the pediatric intensive care unit. John H. Arnold, MD. Pediatr Crit Care Med 2000 Vol. 1, No. 2

Dani et al (Effects of pressure support ventilation plus volume guarantee vs high-frequency oscillatory ventilation on lung inflammation in preterm infants. Pediatr Pulmonol 2006; 41:242-9) recently demonstrated a reduction in lung inflammation in premature neonates randomized to HFOV when compared with patients treated with pressure support ventilation with volume guarantee. Jaballah et al. (High-frequency oscillatory ventilation in pediatric patients with acute respiratory failure. Pediatr Crit Care Med 2006; 7:362-7) also recently reported successful use of HFOV as a rescue technique in paediatric patients who had failed CMV. Mehta et al. (High-frequency oscillatory ventilation in adults: the Toronto experience. Chest 2004; 126:518-27) reported successful use of HFOV as a rescue mode for adults with severe oxygenation failure treated with CMV. Authors also suggested that earlier implementation of HFOV may be beneficial, as number of days of CMV prior to initiation of HFOV was found to be an independent predictor of mortality.

Lung protective ventilation strategies

(For reasoning see under complications of ventilation)

1) lower tidal volume and higher PEEP (*Amato MB et al. Effect of protective-ventilation strategy on mortality in ARDS. N Engl J Med. 1998 Feb 5;338(6):347-54. AND Lower TV-ARDS network*) prevent ventilator-induced lung injury, and optimize oxygen delivery. Old goal of maintaining PaCO₂ in normal range at all costs replaced with realization that large swings in VT → severe lung injury (volutrauma or barotrauma) and ↑ pro-inflammatory cytokines.

2) Improve V/Q mismatch

Prone Positioning

Effect of Prone Positioning on the Survival of Patients with Acute Respiratory Failure. Gattinoni L et al. New Engl J Med 2001; 345:568-573

Different areas of alveolar collapse in dependent lung regions ARDS patients. No prone positioning reports perfect. Addition of treatment that **improves oxygenation** as body attempts to heal itself *just* makes sense. Hard to show mortality change from 1 therapy alone.

Care c pressure areas, makes access difficult. Data supports prone positioning in selected children with ARDS.

Effect of mechanical ventilation in the prone position on clinical outcomes in patients with acute hypoxemic respiratory failure: a systematic review and meta-analysis. Sud et al, CMAJ. 2008 Apr 22; 78: 1153-61. Review.

A Randomized Trial of Prolonged Prone Positioning in Children With Acute Respiratory Failure. Kornecki A et al. Chest 2001 119: 211-218

2) Permissive hypercapnia- (Hickling K et al. Low mortality associated with low volume pressure ltd ventilation with permissive hypercapnia in severe ARDS. *Intensive Care Med* 1990;16:372-377. Hypercapnia: permissive and therapeutic. Kavanagh et al, *Minerva Anesthesiol.* 2006 Jun; 72: 567-76) consequence of ventilation strategy accepting deliberate hypoventilation in order to reduce lung overdistension increase transalveolar pressures within compliant, non-collapsed lung. Potential problem is increased patient respiratory drive, therefore increased need for sedation.

- a) Aim arterial pH ≥ 7.25 ignore pCO_2
- b) Alkalisating maybe step too far

N.B. Avoid in patients with raised ICP.

Detection and management of complications of mechanical ventilation – volutrauma

Evolving concept in ALI and ARDS - iatrogenic lung injury secondary to high tidal volumes (TV) which can lead to overdistension of alveoli. ARDS is a heterogeneous disease with collapse, non-recruited lung adjacent to normal lung. Large TV 10-15 ml/kg, unevenly distributed \Rightarrow overdistension of compliant alveoli \Rightarrow local hyperventilation and surfactant inhibition+depletion. Repetitive opening and closing of recruitable alveoli \rightarrow shearing injury thought to contribute to process.

Injury is due to excess volume but reflected clinically by $\hat{=}$ static or plateau airway pressures. Animal studies suggest transalveolar pressure > 30 mm Hg contributes to significant injury. Correlates to static or plateau airway pressure of 30-40 cm H₂O, depending on chest wall compliance \rightarrow concept of pressure-targeted ventilation which emphasizes lower TV (4-8 ml/kg) in effort to keep static airway pressures in lower range

Principles of weaning from ventilation

http://pedscm.wustl.edu/ejournal_club.html -evidence based weaning reviews

Formal assessment ventilation discontinued if following criteria satisfied:

1. Evidence for some reversal of underlying cause for respiratory failure;
2. Adequate oxygenation (eg PaO_2/FiO_2 ratio > 150 to 200 ; PEEP ≤ 5 to 8 cm H₂O; $FiO_2 \leq 0.4$ to 0.5); and pH (eg ≥ 7.25);
3. Haemodynamic stability
4. The capability to initiate an inspiratory effort.

Criteria	Description
Objective measurements	<p>Adequate oxygenation (eg, $PO_2 \geq 60$ mmHg on $FIO_2 \leq 0.4$; $PEEP \leq 5-10$ cm H_2O; $PO_2/FIO_2 \geq 150-300$);</p> <p>Stable CVS (eg, $HR \leq 140$; stable BP; no (or minimal) pressors)</p> <p>Afebrile (temperature $< 38^\circ C$)</p> <p>No significant respiratory acidosis</p> <p>Adequate hemoglobin (eg, $Hgb \geq 8-10$ g/dL)</p> <p>Adequate mentation (eg, arousable, $GCS \geq 13$, no sedative infusions)</p> <p>Stable metabolic status (eg, acceptable electrolytes)</p>
Subjective clinical assessments	Resolution of disease acute phase; physician believes discontinuation possible; adequate cough

Hgb = haemoglobin; HR = heart rate; GCS = Glasgow coma scale.

Failure to Wean Guidelines

LOAD	DRIVE	CAPACITY OF RESPIRATORY PUMP
Bronchospasm	Sedation	Treat pain and discomfort
Left ventricular failure	CNS disease	Treat abdominal discomfort
Hypercarbia	Optimize position	Sepsis
Look for diaphragmatic paralysis	Seizure Control	Fever Self-esteem
Other causes of increased Basal metabolic rate		Have muscle relaxants worn off?
Is there evidence of:	Consider	Optimize strength
Excessive secretions	Hb	Muscle weakness
Hyperinflation	Anxiety	Neuropathy
	Fear	Disuse atrophy
	Sensory overload/deprivation	Nutrition
	Pleural effusion/pneumothorax	Rest/sleep
		Electrolytes

Interpretation of blood gas

- a) PaO_2 , SaO_2 and O_2 Content -Martin *All You Really Need to Know to Interpret ABGs* 1999 Lippincott Williams & Wilkins
- b) PPT from peds ccm '02_blood_gas' in ICU
- c) NB Stewart's strong ion theory alternative to Henderson-Hasselbach for those of you ever working South of river/on with Sophie S (author 3 on paper!) *The strong ion gap predicts mortality in children following cardiopulmonary bypass surgery. Durward et al. Pediatr Crit Care Med 2005 Vol. 6, No. 3*

Interpretation of CXRs;

Most of these you should already know but **Virtual hospital** explains them at <http://www.radquiz.com/Thoracic-Imaging.htm>

Should we do daily CXR? *Quasney et al Routine Chest Radiographs in PICU. PEDIATRICS Vol. 107 No 2 Feb 2001*

Other sources of information:

Websites. <http://medocs.ucdavis.edu/IMD/420C/esyllabus/ventilat.htm> good intro here
http://pedscm.wustl.edu/EBJournal_club.html evidence based papers

References. See text

Information for Year 2 ITU Training (advanced):

Year 2 ITU curriculum

Ventilation:

- Principles of oxygen delivery systems: pressure regulators, flow meters, vaporizers, breathing systems; disconnection monitors, scavenging systems for waste gases, pipeline and suction systems, Humidification.
- More advanced methods of ventilatory support: non-invasive ventilation (negative pressure jacket) and invasive, positive pressure ventilation using CMV, assist modes, trigger modes, HFOV. Advantages and disadvantages of each mode.
- Lung protective ventilation strategies – improve V/Q mismatch, permissive hypercarbia, low tidal volume, recruitment, IRV.
- Detection and management of complications of mechanical ventilation – volutrauma, oxygen toxicity, inflammation.
- Long-term or home ventilation
- Partial liquid ventilation

Investigations:

- Indications for, risks of and limitations of: spiral /chest CT, ventilation/perfusion scan, bronchograms, bronchoscopy.
- Respiratory function tests: simple tests of pulmonary function e.g. peak flow measurement, spirometry, the pneumotachograph.
- Outcome prediction.

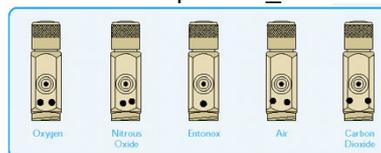
Curriculum notes for year 2:

Ventilation

Principles of oxygen delivery systems

A) Cylinders

- Molybdenum steel -gases and vapours under pressure
O₂ stored as gas at pressure of 13,700 kPa
black body white shoulder for codes see-
(http://www.bocmedical.co.uk/product_information/Cylinder_data_chart.pdf)



- Pin-index valve system
non-interchangeable valves, ensure correct gas into cylinder
cylinder connected correctly hole positions on cylinder valve unique and correspond with pins on yoke attached to equipment
- B) Medical gas pipeline source
primary source for ICU
O₂ produced by fractional distillation of liquid air. Stored as a liquid -150 to -175 degrees C in large flask (liquid occupies 1/860 of space gas would occupy)
Safety systems and regulators send oxygen to the hospital pipeline at approximately 50 psi ("normal working pressure" of anesthesia gas machine)
Non-interchangeable spring loaded valves (Schraeder) inserted into the wall ports



Pressure regulators

Gas and vapour stored under high pressure in cylinders
 Regulator reduces variable cylinder pressure to constant working pressure -around 400 kPa -just under pipeline pressure

Temperature and pressure of cylinder decrease with use, regulator avoids need for constant adjustment to maintain flow

Regulator

Inlet leading to high pressure chamber with valve

Valve leads to low pressure chamber and outlet

Diaphragm attached to spring situated in low pressure chamber

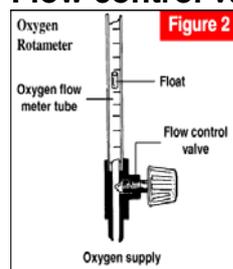
Mechanism

Balance between inlet pressure and springed diaphragm keeps gas flow at 400kPa

Caveats

Diaphragm can rupture

- **Flow control valve (needle valves) and flow meter**



Flow control valve

Manually adjusted

Screw into base of flow meter

Increase gas flow by turning screw anti-clockwise

Flow meter

Calibrated for gas used at room temp and atmospheric pressure -Accurate+- 2.5%

Gravity of bobbin v gas pressure below-constant pressure difference as floats

Measure from top of bobbin, or middle of ball

Bobbin slits make it rotate so know is moving

Low flow meters (NICU) for flow < 1 l/min

Vaporizer

Changes liquid inhalational agent to vapour, adds controlled amount to fresh gas flow

Expressed % of saturated vapour added

Vapour is gaseous state of substance below critical temperature. At room temp and atmospheric pressure substance is liquid. Critical temp is when substance cannot be liquefied no matter how much pressure applied (-118 °C for O₂)

Colour coded

Red-halothane

Purple-enflurane

Purple-isoflurane

Yellow-sevoflurane

Blue – desflurane

Breathing systems- http://www.nda.ox.ac.uk/wfsa/html/u07/u07_013.htm#modd

Components

Reservoir-2 l adults, 0.5 smallest paediatric size

Tubing-corrugated plastic (rubber in anaesthetics)

Various configurations-see Mapleson system

Adjusted pressure relief valve-with 1 l bag ICU

Mapleson system ABCDEF added (REF)

ICU-most commonly used A and F = T-piece system

500 ml bag-open ended (F) for CPAP, scavenging a problem

1 l bag, PEEP via APL –no need scavenge for O₂/air

Disconnect monitors

Pressure monitors in circuit

End-tidal CO₂

Saturation probe- too late!!

Scavenging systems for waste gases (? NO important)

Collects waste gases from ventilator and discards safely

Collection, transfer, receipt and disposal systems

Passive vs active

Passive

Shroud connected to expiratory valve of ventilator and transfer tubing

? Receiving system (eg reservoir bag)

Disposal system –to atmosphere or ventilation system

Active

Same collection and transfer as above

Disposal system is active with fan or pump creating vacuum

Can deal with wider ranges of flow

Others

Ventilation of unit

Use of inhalational agents rare on ICU, ? NO important

Theatre

Local/regional anaesthesia

Circle system

Cardiff Aldasorber (charcoal based passive system)

Pipeline and suction systems

Suction system-airway management/chest drains etc

Portable suction-transfers (in-hospital/intra-hospital)

Centralized vacuum system

Pump, reliever and filter

Pump

creates negative pressure of 400mmHg

Accommodates air flow of 40 l/min

Recommended 1 outlet per bed

Humidification

Dry gas damages respiratory epithelial cells Susceptibility to LRTI

Temperature instability-loss of latent heat of vaporisation

a) Heat and moisture exchange humidifiers (HME) (CATS/transfer)

Small, cheap, effective and no need for external power source

Inspired gases warmed to 30-34°C

Relative humidity 60-70% ie adequate

Adds condensation and heat of patients exhaled gas to next inspired breath

HMEF include anti-bacterial filter

Increases dead space

Affected by tidal volume, gas temperature, flow rate etc

b) Hot water bath humidifier (More usual on ICU)



More effective than HME

Gas inlet/outlet thermostat Tubing and water trap (put lower than pt)
Large surface area so most gas fully saturated and heated 37°C
Thermistor near ETT allows feedback loop
Bacterial colonization/risk of scalding
Needs electrical power cf HME

- **More advanced methods of ventilatory support: non-invasive ventilation (-ve pressure jacket) and invasive, positive pressure ventilation using CMV, assist modes, trigger modes, HFOV. Advantages and disadvantages of each mode.**

Hayek Negative pressure CPAP/oscillate -better cardiopulmonary interaction.

Constant negative pressure throughout the respiratory cycle increases functional residual capacity (FRC) and is equivalent to a positive end expiratory pressure produced inside the airway.

NPV causes inhibition of respiratory muscle activity, decreasing in both diaphragmatic electrical activity and mechanical activity of the diaphragm, with significant decrease in the work of breathing.

We have also used in attempt to not intubate eg muscular problems, and also occasionally with intubated patient synchroed to aid cardiac output. In patients with the Fontan circulation the absence of a right ventricle, means that pulmonary blood flow, the major determinant of cardiac output, is a passive diastolic phenomenon, enhanced as the pleural pressure becomes negative during spontaneous inspiration, but reduced or even zero when the intrathoracic pressure is made more positive. By mimicking spontaneous respiration, negative pressure ventilation augments the cardiac output of Fontan patients to levels that are unrivalled by other forms of treatment.

Disadvantages: as good seal is necessary around the patient, it is important to protect the skin at contact points and avoid venous obstruction. Occasionally observed is extrathoracic upper airway obstruction due to suppression of the normal pre-inspiratory activation of upper airway muscles, rendering upper airway structures floppier and more susceptible to passive closure. Can be overcome by nCPAP/fm IPPV.

Modes

Suppression of spontaneous breathing and complete dependence on mechanical ventilation
→ respiratory muscle atrophy –so modes allowing spontaneous breathing or patient-triggered modes favoured when feasible

Assist/Control Mode Ventilation

Combined mode of ventilation. Ventilator delivers positive pressure breath of predetermined TV in response to each inspiratory effort (*assisted ventilation*).

If pt fails to initiate breath within a specific time period, ventilator automatically delivers a mechanical breath to maintain minimum or “backup” respiratory rate (*controlled ventilation*). To trigger assisted breath must lower airway pressure by preset amount- the *trigger sensitivity*.

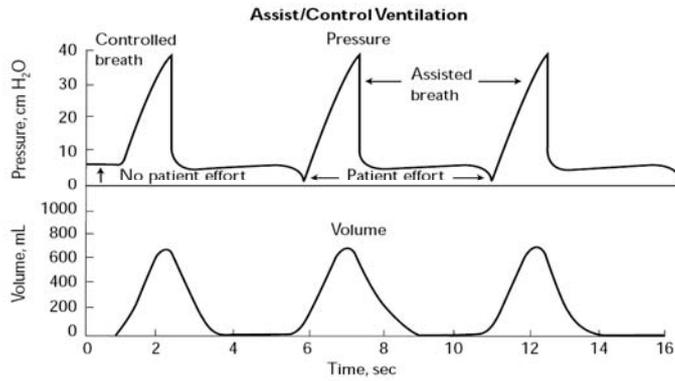


Figure 1. Pressure and volume waveforms during assist/control ventilation. Note that the first breath is provided by the ventilator without any patient trigger (controlled breath) and the second and third breaths are triggered by the patient (assisted breaths). H₂O = water.

Advantages: Assist-control ventilation ensures the security of controlled ventilation and allows synchronization of the breathing rhythm of patient and ventilator, and it ensures ventilatory support during every breath.

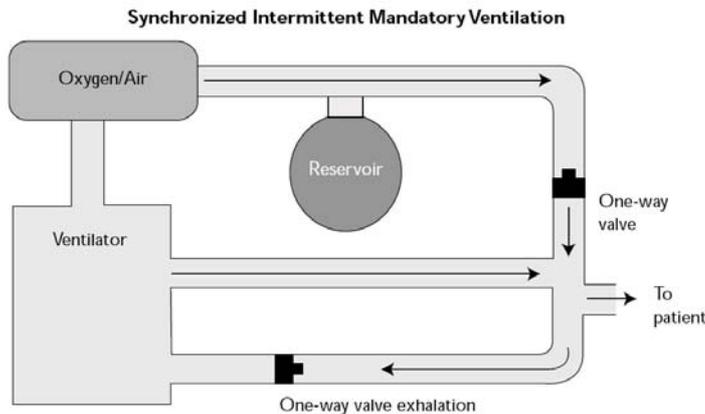
Disadvantages:

1. Excessive patient work may occur if inadequate peak flow or sensitivity setting, especially for pts with increased ventilatory drive
2. It may be poorly tolerated in awake, non-sedated subjects and can require sedation to ensure synchrony;
3. It may be associated with respiratory alkalosis due to excessive triggering of ventilator by anxious patient
4. It may potentially worsen air trapping in patients with COPD.

Synchronized Intermittent Mandatory Ventilation

Mandatory number of positive pressure breaths per minute, each synchronized to patient effort. Ventilator detects initiation of spontaneous breath and does not deliver machine breath during a spontaneous breath.

Between mechanical breaths may breathe an indefinite number of times from reservoir



Spontaneous breaths produce no response from the ventilator.

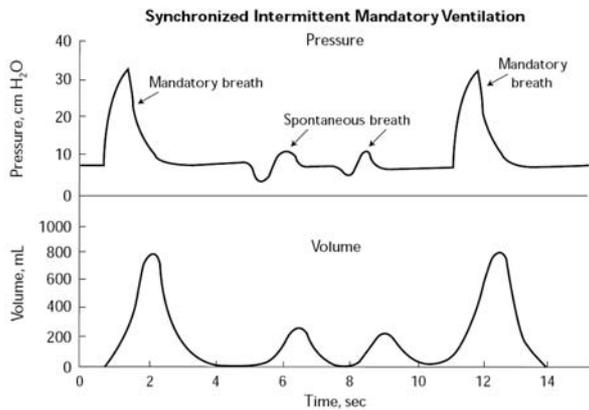


Figure 3. Pressure and volume waveforms during synchronized intermittent mandatory ventilation. Note that the first and last breaths are mandatory and the second and third breaths are spontaneous. H₂O = water.

Advantages:

1. Pt able to perform variable amount of respiratory work with security of preset mandatory level of ventilation;
2. Allows for variation in support-full support to spontaneous breathing
3. Useful weaning mode.

Disadvantages:

1. Dysynchrony between pt effort and machine-delivered volume can occur especially with inadequate flow rates;
2. Hyperventilation and respiratory alkalosis possible, similar to A/C;
3. Excessive work of breathing during spontaneous breaths can occur due to presence of poorly responsive demand valve or inappropriate flow delivery;
4. May potentially worsen air trapping with asthma.

Pressure-Support Ventilation

With each spontaneous breath the negative pressure or flow in inspiratory circuit opens valve → ventilator delivers flow of gas sufficient to maintain a constant inflation pressure. When inspiratory flow rate falls below preset threshold, flow of gas terminates. Patient controls respiratory rate and inspiratory time and flow. TV + minute ventilation partly determined by patient + partly by ventilator. TV received depends on set level of pressure support, patient effort, and the pulmonary mechanics. Pressure support may also be applied to a patient's spontaneous breathing during SIMV

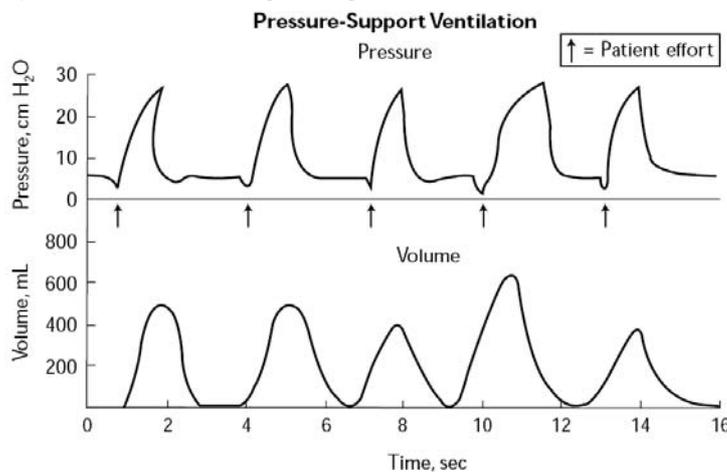


Figure 4. Pressure and volume waveforms during pressure-support ventilation. Note that each breath is triggered by patient effort. The breaths vary in tidal volume and inspiratory time. H₂O = water.

Advantages:

1. Most spontaneously breathing pts comfortable with little dys-synchrony.

2. Work of breathing ↓ in proportion to delivered pressure and associated with ↓ respiratory frequency and ↑ TV with ↑ levels of PS.
3. PS can be used to compensate for extra work produced by ETT and demand valve.
4. Allows wide variation in level of partial ventilatory support from nearly total support (high pressure levels) to essentially spontaneous breathing. Hence useful as weaning tool.

Disadvantages:

1. Tidal volume dependent on respiratory mechanics, cycling frequency, and patient-ventilator synchrony. Hence need careful monitoring for unstable patients and back-up minute ventilation needed for safety.
2. Pressure support ventilation may be poorly tolerated in some patients with high airway resistance because of the preset high initial flow and terminal inspiratory flow algorithms. This may be improved, however, with adjustment of initial flow rates.

Others

Pressure Control Ventilation (PCV)

PCV more popular as recent attention focused on minimizing static airway pressures in ARDS patients. PCV involves setting target airway pressure on ventilator which then delivers rapid flow to that set pressure with a square pressure wave form. TV depends upon compliance and can vary as condition improves or deteriorates. Flow curve for pressure control is decelerating curve ? some advantages over volume-cycled ventilation in maintaining recruited alveoli and thus improving oxygenation.

Advantages:

1. Airway pressures uniformly controlled by set pressure limit thus minimizing overdistension
2. Decelerating flow curve ? allows improved oxygenation by optimizing alveolar recruitment

Disadvantages:

1. Can be an uncomfortable mode of ventilation and thus require significant sedation
2. TV varies with compliance → close monitoring avoid excessive/inadequate ventilation

Pressure regulated volume control (PRVC)

Good alternative to PCV if rapidly changing compliance -Remains a pressure regulated approach but pressure varies to maintain given tidal volume. Uses decelerating flow curve of pressure control so maintains this advantage while avoiding complications of excessive or inadequate ventilation as lung compliance changes

Airway Pressure Release Ventilation (APRV)

Spontaneous breathing with CPAP interrupted by short (1-1.5s) releases of pressure to augment expiration. Moderately high airway pressure (20-30 cm H₂O) most of the time, thereby keeping alveoli open. Unique in that ventilation is enhanced by reduction rather than increase in lung volume. During short expiratory release PEEP remains present to keep alveoli with slow time constants open as well (Schultz TR, Costarino AJA, Durning SM, et al. Airway pressure release ventilation in pediatrics. *Pediatr Crit Care Med* 2001; 2:243–246).

Advantages:

1. Preservation of spontaneous breathing -may improve comfort + decrease sedation need
2. CPAP useful in keeping alveoli open
3. A short expiratory time which favours ventilation of fast compartments
4. Reduced barotrauma risk
5. Relatively low airway pressures - ↓ volutrauma, improve pulm'ry circulation + O₂ delivery

Disadvantages:

1. Very short expiration times can lead to incomplete exhalation of slow compartments of the lung which can lead to the development of auto-PEEP secondary to breath stacking
2. Requires spontaneous respiratory drive ? associated with ↑ work of breathing
3. Dead space ventilation may be relatively increased due to lower tidal volumes
4. Potential for de-recruitment and atelectrauma during intermittent pressure releases

Inverse Ratio Ventilation (IRV)

Refers to altering the I:E ratio such that the inspiratory time exceeds the expiratory time. A normal I:E ratio is 1:3. Usually used in conjunction with a pressure control mode for severe pulmonary disease and profound hypoxia. Can be applied to volume cycled ventilation by ↓ inspiratory flow rate and applying decelerating flow curve. ↑ inspiratory time allows for enhanced recruitment of collapsed alveoli which should improve oxygenation. Extremely uncomfortable mode of ventilation and thus requires high levels of sedation

Advantages:

1. Improved oxygenation -allowing less time for alveolar collapse and longer inflation time
2. Decreased dead space ventilation, allowing use of a smaller TV
3. ↓ peak airway pressures without compromising minute ventilation.

Disadvantages:

1. Severe pt discomfort needs high levels of sedation often paralytics
2. Short expiratory time can lead to breath stacking and auto-PEEP
3. Increased auto-PEEP may be associated with increased risk of barotrauma, and haemodynamic effects on right heart filling.

High Frequency Oscillation (HFOV)

<http://www.frca.co.uk/article.aspx?articleid=100411>

<http://www.draeger-medical.co.uk> (please note that the waveform diagrams have been taken from this website)

Advantages:

- Enables stable lung inflation
- Allows recruitment of alveolar space
- Reduces the risk of volu-trauma
- Reduces risk of high peak airway pressure
- Reduces the risk of airway stretching
- Improves V/Q matching

Disadvantages:

- inadvertent PEEP
- Necrotizing Tracheo-bronchitis (NTB)
- Expose hypovolaemia/impaired cardiac function
- Patient ventilator interaction

Loads of papers on use:-

- www.sccm.org/specialties/pediatric/picu_course/Documents/catalog_pdf/03_high_frequency_oscillatory_vent.pdf
- Arnold JH, Hanson JH, Toro-Figuero LO, Gutierrez J, Berens RJ, Anglin DL. Prospective, randomized comparison of high-frequency oscillatory ventilation and conventional mechanical ventilation in pediatric respiratory failure. *Crit Care Med.* 1994;22(10):1530-9
- Derdak S, Mehta S, Stewart TE et al. High-Frequency Oscillatory Ventilation for Acute Respiratory Distress Syndrome in Adults. *Am J Resp Crit Care Med* 2002; 166:801-808

Lung protective ventilation strategies –

1-3 see year 1

4) Recruitment -(Rimensberger P et al. Lung recruitment and lung volume maintenance: strategy for improving oxygenation and preventing lung injury during both conventional mechanical ventilation and high-frequency oscillation. *Intensive Care Med.* 2000 Jun;26(6):745-55)

<http://www.medscape.com/viewarticle/427184> How the Experts Ventilate Patients With ARDS
Concept of re-inflating atelectatic aveoli, maintaining above FRC to prevent cyclical collapse
Review of ARDS adult recruitment (*Lung Recruitment + Setting of PEEP*)
www.imhotep.net/kacmarekr.html

5) Inversed ratio ventilation (IRV)-see above under modes

6) Improving V/Q matching-see year 1

7) Others

Surfactant - **Willson DF** (*Effect of exogenous surfactant (calfactant) in pediatric acute lung injury: a randomized controlled trial.*, *JAMA.* 2005 Jan 26;293(4):470-6) showed a reduction in mortality with two doses of calfactant in the first 24 hrs, however multivariate analysis, revealed that this mortality difference was not statistically significant once adjustments were made for the immune status of the patients.

INO – reverses V/Q mismatch seen in ARDS by selectively mediating pulmonary vasomotor tone in well ventilated lung units and subsequently reducing increased pulmonary vascular resistance and pulmonary hypertension. A meta-analysis (Inhaled Nitric Oxide for Acute Hypoxic Respiratory Failure in Children and Adults: A meta-analysis, Jennifer Sokol, *Anesth Analg* 2003;97:989 –98) suggests that INO transiently results in improved oxygenation in ARF, with no discrepancy between small or large doses, but that it has not demonstrated a significant effect on mortality. However most trials are poorly conducted.

Detection and management of complications of mechanical ventilation – volutrauma, oxygen toxicity, inflammation.

Significant complications associated with mechanical ventilation complications include: oxygen toxicity, alveolar stretch injury or volutrauma, barotrauma, patient-ventilator asynchrony, nosocomial pneumonia, and adverse effects on cardiac function and output.

1. Oxygen Toxicity:

Recognized for years that high FiO_2 commonly used during mechanical ventilation can cause iatrogenic lung injury. Pathophysiology underlying these changes can be divided into 2 categories: alteration of normal physiology and oxygen-induced tissue injury.

a) Alterations in normal pulmonary physiology

include: depression of ventilation, vasodilation of pulmonary vasculature, ↓ production of surfactant, and absorption atelectasis- (from wash out of the normal concentration of alveolar nitrogen which acts as a splint to keep alveoli open during expiration). Effect most prominent in severe parenchymal lung disease can exacerbate intrapulmonary shunting.

b) Toxic reactive O_2 species which cause free radical damage to lung tissue.

→ disruption of pulmonary capillary endothelial cells and alveolar epithelial cells which alters permeability → interstitial oedema. Degree of injury depends upon a number of factors including FiO_2 and duration of exposure. Normal lungs may tolerate FiO_2 up to 0.60 whereas injured lung may be damaged at concentration greater than 0.50.

Estimated oxygen toxicity clinically significant when exposure > 8 -12 hours → trend toward lower FiO_2 in conjunction with increased use of PEEP to maintain oxygenation has developed

2. Volutrauma / Stretch Injury:

See year 1

3. Barotrauma:

Includes development of pneumothorax, pneumomediastinum, pneumopericardium, air cysts, pulmonary interstitial emphysema, intraparenchymal tension cavities, and systemic gas embolism.

Barotrauma most common with severe parenchymal injury ie ARDS. Ongoing debate concerning relationship high ventilatory pressures and barotrauma as recent studies unable to define a clear relationship between elevated PIPs and pneumothorax.

More relevant may be transpulmonary pressure which is alveolar pressure minus the pleural pressure -supported by observation very high airway pressures often reached without barotrauma. Important, however, to maintain a high index of suspicion for development of barotrauma, as tension pneumothorax can be a life-threatening

4. Patient-Ventilator Asynchrony:

Occurs primarily in patients receiving partial ventilatory support. Inappropriate triggering, flow delivery, and cycling criteria on the ventilator can cause significant imposed load and discomfort resulting in need for substantial sedation. Particularly important when using alternative modes of ventilation which can be extremely uncomfortable eg PCV and IRV

5. Nosocomial Pneumonia:

Prolonged endotracheal intubation leads to alteration in normal endo-bronchial flora → increased susceptibility to lower tract infection. Nosocomial pneumonia is one of the most serious complications that can occur with mechanical ventilation and significantly delays weaning and lengthens ICU stay

6. Effects On Cardiac Function: See cardiopulmonary interaction with PPV

Long-term or home ventilation

Usually under respiratory team - TCU/resp ward :-

Temporary eg malacia, CLD (months) diaphragmatic paralysis-(? years)

Permanent eg high spinal cord lesion

- Intermittent eg nocturnal face mask BiPAP
- continuous -tracheostomy and Sullivan/Breeze

Partial liquid ventilation

Ventilating with conventional ventilation after filling with perfluorocarbon

Eg perflubron

20 times heavier than O₂ + heavier than water

higher spreading co-efficient

animal models suggest improved compliance and gas exchange

Poor results so on hold at GOSH

? Some new lung growth Glasgow in ECMO for CDH

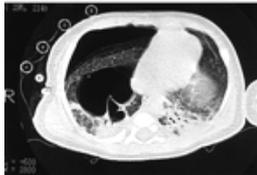
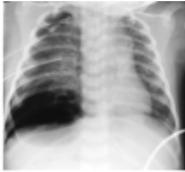
Indications for, risks of and limitations of: spiral /chest CT, VQ scan, bronchograms+bronchoscopy

Spiral /chest CT

Indication-failure to wean etc; Risk- transport to CT, radiation vs diagnosis/

Limitation-need for transfer-often on HFOV/prone etc

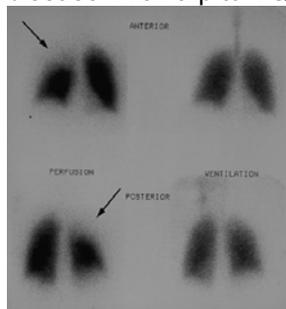
Eg missed PTX



(Thomas et al .Efficacy chest CT in PICU. *Chest*.2000;117:1697)

Ventilation/perfusion scan

Indications-R/O PE, delineate congenital lung disease pre-op, investigate diffuse lung disease /Risk-trip to VQ/limitations-technical



?PE



V/Q scan -air trapping and decreased perfusion lower 2/3 Rt lung= Congenital Lobar Emphysema, Right Middle Lobe

(<http://erj.ersjournals.com/content/vol18/issue3/images/large/erj180589-1.jpeg>)

Bronchograms

Indication-investigation tracheobronchial malacia or stenosis, routine investigation pre-tracheal surgery at GOS-assess **dynamic feature** of obstruction

- Inwald D et al. *Current Mx + outcome TBM + stenosis presenting PICU. INTENSIVE CARE MED.*27/4(2001)722-9
- Elliott et al. *Mx congenital tracheal stenosis. Int' Congress Series 1254 (2003) 321–33*

Bronchoscopy in PICU.

Andy Bush et none. *Bronchoscopy in paediatric intensive care. Paediatric Respiratory Reviews. Volume 4, Issue 1* , March 2003, Pages 67-73)

Indications -endobronchial toilet, instilling recombinant human DNAase (even non-CF children) checking tube patency and position; assisting difficult intubation or tube change; selective intubation of a main bronchus; diagnosis and management of ventilator-associated pneumonia or the ventilated, immunocompromised host; the assessment of lobar collapse or focal hyperinflation; airway stent assessment; assessment of stridor on extubation and the diagnosis of any associated disease

Respiratory function tests: simple tests of pulmonary function e.g. PEFR, spirometry, pneumotachograph and other respirometers

Respiratory monitoring tools in the intensive care unit attached

Non-invasive respiratory monitoring in paediatric intensive care unit attached

Basic forms should be familiar from base speciality

Outcome prediction.

1) Dahlem et al. *Incidence and short-term outcome of acute lung injury in mechanically ventilated children. Eur Respir J.* 2003 Dec;22(6):980-5.

2) Marcin et al. *Certainty and mortality prediction in critically ill children. J Med Ethics* 2004;30:304–307. doi: 10.1136/jme.2003.001537

Other sources of information: http://pedscm.wustl.edu/FILE-INET/File_cab_index.html
s of stuff