General anesthesia promotes « Lung heterogeneity »

How to address the challenges in anesthesia

Outline
- Physiological characteristics
- Physiological effects on the lung
- Cardio-respiratory interaction
- Physiology effects and monitoring

Positive pressure ventilation has a cost on various physiological variables

Cardiovascular system
- Pulmonary system
  - Compresses capillaries after perfusion
  - Venous return
- Lymphatics
  - Lymphatic flow

Variable compliance-dependent ventilation
- Effect on surfactant
- Alter compliance
- Ventilation/Perfusion

Respiratory system
Passive system (exchanger)
- Airways:
  - RESISTANCE: flow
  \[ R = \frac{\Delta P (P2-P1)}{\text{Flow}} \]
- Lungs - Alveoli:
  - COMPLIANCE: Volume
  \[ C = \frac{\text{Volume}}{\Delta P (P2'-P1')} \]

Active system (pump)
- Respiratory muscles
  (diaphragm, accessory muscles...)

I have no COI to disclose

Physiology of Assisted Ventilation
Walid Habre, MD, PhD
Anesthesiological Investigations Unit
& Pediatric Anesthesia Unit
Geneva University Hospitals and University of Geneva
www.walidhabre.org

I have no COI to disclose
Impedance of the respiratory system

**Elastic forces**
- Necessary for the distension of an elastic structure
- Elastance (1 / Elastance)

**Inertance**
- Resistance resulting from tissue distortion

**Resistive forces**
- Resistance to air flow

**Elastance**

**Molecular**
- Surfactant
- Surfactant interperses the water molecules
- Reduces surface tension
- Lung stability

**Morphology**
- Extracellular matrix
- Baseline membrane
- Collagen
- Fibroblast cells
- Proteoglycans

**Function**
- Low strain
- Increase strain
- Coupling of the elastic and dissipative properties
- Viscoelasticity of the lung

**Haemodynamic**
- DIRECT EFFECT
  - Mechanical interdependence
- INDIRECT EFFECT
  - Regulatory mechanism (mediators, neuronal control)
  - Abrupt change in lung haemodynamics
  - Change in the mechanical properties of the lung

- Elastin
- Collagen
- Coupling of the elastic and dissipative properties
- Viscoelasticity of the lung
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Postoperative respiratory complications

Hypoxemia
- Decrease DO
- Ischemia-reperfusion lesions
- Delirium
- Wound infection
- Arrhythmias/myocardial ischemia

Pneumonia
- Macrophages dysfunction
- Surfactant depletion
- Bacterial development
- Bacterial Translocation

Local inflammatory response/\*VILI
- Local Hypoxia/hyperoxia
- Local mechanical parenchymal stress/shear stress
- Rettinma
- Cyclic recruitment
- Alveolar distortion

\*VILI: « ventilator induced lung injury »

Factors contributing to lung injury

- Positive pressure effects on intrathoracic pressures
- Pressure and distribution of airflow into the alveoli
- Pressure, stretch, and the lung
- Surfactant functions
100% FiO₂

Pressure gradient
Intraalveolar-capillaries
Rapid diffusion of O₂ across alveolar-capillary barrier
Loss in alveolar distending pressure

Elevated FiO₂ at induction leads to rapid alveolar collapse independent of the carrier gas

Atelectasis by O₂-absorption

The kinetic of O₂-absorption atelectasis is determined by the alveolar concentration

The effect of gas composition on the recurrence of atelectasis after re-expansion

After RM, 40% FiO₂
- delays significantly the recurrence of atelectasis (at least 40')
- V/Q
- relative perfusion to poorly ventilated lung units

Consequences of low FRC
Airway closure
Increased airway resistance
Impaired gas exchange
Increased work of breathing

Repetitive intermittent stretch or constant stretch stimulates greater release of inflammatory mediators?

Cyclic opening and closing from ZEEP:
Greater increases BAL cytokines than atelectasis.

High-volume ventilation, over time:
Degree of overdistension is more associated with increases in BAL cytokines than cyclic opening and closing alone
Cyclic opening & closing
Stress and shear forces

Over-distension of alveoli

Increased cytokine production
Increase white cell sequestration

Notion of Energy load to the respiratory system and dynamic alveolar strain

Energy load to the respiratory system comprises:
- A static component, due to PEEP and PEEP volume (potential energy):
  \[
  \text{Static energy load} = \text{PEEP} \times \text{PEEP volume}/2
  \]
- A dynamic cyclic component, due to driving pressure and tidal volume above PEEP (kinetic energy):
  \[
  \text{Dynamic energy load} = (\text{PEEP} + \text{Peak pressure}) \times \text{TV}/2
  \]
  \[
  = (\text{Peak pressure} - \text{PEEP}) \times \text{TV}/2 + \text{PEEP} \times \text{TV}
  \]

Protti A et al. Int Care Med Exp 2015; 3:34

In healthy lungs, PEEP is protective only if associated with a reduced tidal volume otherwise, it has no effect or is harmful

Lower limit of inspiratory capacity = threshold for VILI
The dynamic component impact VILI
Above inspiratory capacity stress rupture may occur

Average inspiratory capacity:
TLC-FRC

Innovative concept: Role of driving pressure

Odds of postoperative pulmonary complications according to response of driving pressure after increase of PEEP


Driving pressure = specific tidal volume
‘Specific’ tidal volume
Tidal volume standardized for the end-expiratory lung volume

VT/Crs

VT/EELV

STRAIN
**Optimal PEEP**

- **PEEP** or **Driving pressure**
  - No lung recruitment
  - Lung tissue overstretched

- VT Constant

- Lung recruitment & **Driving pressure**
  - & **aerated lung tissue**

**K-edge subtraction synchrotron imaging:** allows assessment of STRAIN

- Mass attenuation $\mu/\rho$ (cm$^2$/g)
- Inonization energy of Xenon

**Regional lung Ventilation and Blood Volume**

- are heterogeneous in normal lung

- The color codes represent the specific ventilation
- The Coefficient of variation reflects spatial ventilation heterogeneity
- Time constant of alveolar units to fill and empty Xenon

- Demonstration of small length-scale heterogeneity of regional ventilation and perfusion

**Mechanical ventilation with injurious conditions**

- Alteration number and size of LC domain structures at the air–liquid interface

**Mapping of regional ventilation in the lung**

- Baseline
  - Surfactant depletion

**Assessing strain from regional ventilation during VCV and PRVC**

- PEEP 3
  - PEEP 9
  - PEEP 3
  - PEEP 9
  - PEEP 3
At low tidal volume: 7ml/kg & PEEP of 5 cmH₂O

Similar regional strain between VC and PRVC

Clinical implications

Titrating PEEP and VT
Optimize gas exchange
Keeping driving pressure ideally below 13 cmH₂O

Peak airway pressure is lower with a decelerating flow

High end-inspiratory airway pressure
Limited and constant inspiratory pressure

Difficulties to obtain equilibrium between Paw and Palv
Plateau pressure reached quicker
Allows enough time for equilibrium

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Mechanical Ventilation-Induced Intrathoracic Pressure Distribution and Heart-Lung Interactions

Baseline volume status
Cardiac pump function
Vasomotor tone
Cardiopulmonary interaction variability
Effect of positive pressure on venous return
Venous return is proportional to the gradient pressure:
Mean systemic pressure minus the right atrial pressure (Vs – PRA

\[
\text{Venous return} = \text{Gradient pressure} = \text{Mean systemic pressure} - \text{Right atrial pressure}
\]

PEEP alters venous return curve by increasing the upstream pressure

\[
\text{Venous return} \text{ vs. Right atrial pressure}
\]

Hemodynamic effects of mechanical insufflation
RV preload
IVC flow
PEEP alters venous return curve by increasing the upstream pressure

\[
\text{RV preload} \quad \text{RV afterload} \quad \text{LV preload} \quad \text{LV afterload}
\]

Systolic pressure
Pulse pressure
Aortic blood velocity
Minimum at the end of the inspiratory period
Minimum during the expiratory period

Pressure-Volume loops

\[
\text{PPV} \quad \text{cardiac volumes}
\]

Effect of positive-pressure ventilation on cardiac chamber volumes

\[
\text{PPV} \quad \text{cardiac volumes}
\]
Respiratory variation and cardiopulmonary interactions

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The slope of phase III is closely related to the ventilation/perfusion ratio of the lungs

Continuous rising CO2 rather than plateau indicates a V/Q abnormality

\[ \text{CO}_2 \text{ production} \]

\[ \text{Minute ventilation} \]

\[ \text{Distribution volume} \]

\[ \text{Venous return} \]

\[ \text{Capnograph phase III slope} \]

\[ \text{Peták F et al. Eur Respir J 2010; 36s, 54: 944s.} \]

The Raw - $\alpha_{III}$ relationship is influenced by the elastic recoil of the respiratory system

High sensitivity in case of small respiratory elastance
Emptying of the alveoli is determined by the small airway geometry:
- at low lung volumes/pressures: sequential
- at high lung volumes/pressures: parallel

Low sensitivity in case of stiff respiratory tissues
Lung emptying is parallel, determined by the high elastic recoil independently of the small airway geometry

Components contributing to the impedance of the respiratory system
- Elastic forces:
  - Distension of an elastic structure
  - Elastance (E) and Compliance (1/E):
    \[ \text{Crs (ml/cmH}_2\text{O)} = \frac{\text{Volume}}{\text{Pplat-PEEP}} \]
- Resistive forces:
  - Resistance to airflow:
    \[ \text{Rrs (cmH}_2\text{O.L}^{-1}.\text{s}) = \frac{\text{PIP-Pplat}}{\text{Flow}} \]
- Inertive forces:
  - Pressure required to accelerate and decelerate the intrapulmonary gas (important at high frequencies)
Pression-Volume curve: Expresses the mechanical properties

Dynamic pressure-volume curve includes the resistive and convective acceleration components of the flow

Analysis of airway pressure wave during VCV
Strictly in constant flow mode

Estimate changes in Crs and Rrs from the pressure curve analysis

Use flow/time curves to set Ti and Te: reflects recruitment and total exhalation

Large regional variation in both recruitment and over-inflation within and between the lungs
Alveolar recruitment and derecruitment take place at different pressures, and the use of deflation limbs of P-V curves has greater inference to alveolar derecruitment than inflation limbs.

**Apply a « Lung Protective » strategy**

- Target a tidal volume of 6-7 ml/kg based on ideal weight
- Avoid increase driving pressure: VT/EELV
- Restore FRC and optimize PEEP by assessing driving pressure
- Allow permissive hypercapnia: 6 kPa

**Protection of the lung against the harmful effects of positive pressure ventilation could be more important than optimising gas exchange**

**Predicting fluid responsiveness in children: is it realistic?**

- The Starling curve: does it exist in neonates?
  - YES! But it is shifted to the left
- Are classical static variables reliable?
  - No! Very poor predictors
- Dynamic variables derived form heart-lung interaction: are they good predictors?
  - Value of Aortic Peak Flow velocity

**The use of heart-lung interactions during mechanical ventilation to assess fluid responsiveness**

- Systolic pressure variation (SPV)
- Pulse pressure variation (PPV)
  - derived from analysis of arterial waveform
- Stroke volume variation (SVV)
  - derived from pulse contour analysis

**Comparison of the areas under the ROC curve for dynamic variables**

- Aortic Peak Flow Velocity
Monitoring oxygenation and Cardiac output
Importance of assessing adequacy of tissue oxygenation

Goal-Oriented approach

Intravascular volume
Blood Pressure
Cardiac output

Oxygen delivery index
optimize oxygen transport

Improve outcome in high risk patients

Soni N. Br J Anaesth. 2008;101:446-57