Artificial Lung Ventilation

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ESEM Summer School, Trinity College, Dublin, June 22, 2009

Karel’s principle:
If you breathe, you inspire.
If you don’t, you expire!

Khosrow’s principle:
Each single breath brings you closer to the death.
But not breathing is also not a solution!

Conclusion:
It is very hard to help severe diseased lungs without causing additional trauma, but not hopeless!

Artificial Lung Ventilation
Artificial Lung Ventilation

-- Is there anything to solve?

Yes.
Mortality in ARDS respiratory failure

Meta-analysis, 4,966 studies from 1984 till 2006, 89 included
Overall mortality: 44%
Mortality improved after 1994
Since 1994: for RCTs 36%
for observational studies 44%


ARDS (in adults)

ARDS – Adult (or Acute) Respiratory Distress Syndrome

Pulmonary ARDS
Bacterial, fungal, viral, parasitic pneumonia
Aspiration of gastric content
Pulmonary contusion, severe thoracic trauma
Inhalation injury (toxic gases, smoke)
Near-drowning
Fat emboli

Extrapulmonary ARDS
Severe sepsis
Severe no-thoracic trauma
(multiple long bone fractures, hypovolemic shock)
Hypertransfusion
Drug overdose
Acute pancreatitis
Cardiopulmonary bypass

Artificial Lung Ventilation = Mechanical Ventilation, MV

By mechanical ventilation we do not heal the lungs, but we damage them.
Mechanical ventilation only gives the organism sufficient (?) time to heal the lungs (or the cause of the respiratory failure) by itself.

Mechanical ventilation may cause VILI: Ventilator-Induced Lung Injury.

Functions of the Respiratory System

- Pulmonary Ventilation
- External Respiration
- Transport
- Internal Respiration

Partial Pressure of Gases

Partial Pressures of gases

Dalton Law

1 Torr = 1 mm Hg = 0.13 kPa

Structure and pressures

Pneumothorax
Healthy lung
Structure and pressures

- Parietal pleura (pleura parietalis)
- Visceral pleura (pleura visceralis)
- Interpleural space filled with liquid
  - Collapsed right lung

Artificial lung ventilation is "Non-physiological"

- Pneumothorax Healthy lung

Artificial lung ventilation is "Non-physiological"

- Inspirium

Pneumothorax Healthy lung

Artificial lung ventilation is "Non-physiological"

Iron lungs
Origins of VILI

- Volumotrauma (overdistention causes both epithelial and endothelial damage)
- Barotrauma (overpressure in the alveolar unit causes air leakage)
- Atelectrauma (force injury from cyclic end-expiratory collapse of alveoli)
- Biotrauma (release of inflammatory mediators that can also lead to multiple organ failure (MOF) on a systemic level)

Main approaches to MV

1. Traditional Conventional Mechanical Ventilation (Traditional CMV)
2. Protective Conventional Mechanical Ventilation (Protective CMV)
3. High-Frequency Oscillatory Ventilation (HFOV)
4. Mid-Frequency Conventional Mechanical Ventilation (Mid CMV)

Artificial Lung Ventilation - Recent Development

Because patients who die with ARDS usually die from MOF rather than hypoxaemia, strategies to reduce VILI continue to be employed in an attempt to reduce mortality.

Aims of the „modern“ ventilatory support: Prevention, early recognition, intervention and minimising of VILI.
Traditional CMV

Hi tidal volumes ($V_T > 10 \text{ mL/kg}$), zero or insufficient PEEP, no $P_{plat}$ limitation

Large tidal volumes are associated with increased protein leak, lung injury and mortality.


Allowing the lung to remain atelectatic causes biotrauma and can induce multiple organ failure (MOF)


Pressure-Volume Loop and safety of artificial ventilation

Volume ($V$)

Pressure ($P$)

Protective CMV – a RCT

The ARDSnet study found a statistically significant reduction in the 28-day mortality rates in the low tidal volume group (e.g. 40% in 12 mL/kg group vs. 31% in the 6 mL/kg group)


Protective CMV

Low tidal volumes (~6 mL/kg) to prevent overdistension, => relatively high RR (Res. Rate)

Relatively high PEEP (theoretically > lower inflection point of P-V curve) to avoid underdistension (atelectasis and cyclical airway collapse)

Limit plateau pressure to < 32 cm H$_2$O

Enough but limit oxygen, tolerate hypercapnia

Attain and maintain lung recruitment

The Recruitment Manoeuvre

Unfortunately, in practice, many critically ill patients with ARDS are unable to achieve adequate gas exchange using conventional lung protective strategies (esp. $\text{FiO}_2 \leq 60\%$ with $P_{plat} \leq 30 \text{ cmH}_2\text{O}$), and the mortality is still extremely high.

High-Frequency Oscillatory Ventilation in Adults

- Very high RR (> 2 Hz, typically 5 Hz)
- Very small tidal volumes of 1–2 mL/kg
- Safe in delivering ‘super PEEP’ with the distending pressure up to 45 cm H₂O (small VT do not increase PIP significantly)
- Oscillations => significant pressure swings in ETC are attenuated at the alveolar level – low enough to maintain a high distending pressure throughout the respiratory cycle to minimise derecruitment and alveolar collapse.

The Recruitment Manoeuvre

- HFOV is uniquely suited to the goals of limiting overdistention and preventing derecruitment.
- The ability of HFOV to maintain an open lung approach using lower peak airway pressures and smaller tidal volumes compared with conventional ventilation may potentially result in less biotrauma, reducing its systemic effect on other organs, and thereby reduce morbidity and mortality.

High-Frequency Ventilation – evidences

- Safe and effective in adults with severe ARDS who fail conventional ventilation (rescue).
- Significant and prompt improvements in oxygenation, allowing a decrease in FiO₂.
- Produces less histological damage and lower circulating cytokine levels when compared with a high PEEP, low stretch CMV.
- But: No evidence of reduction in mortality.
Mechanisms of Gas Transport

1. direct bulk flow
2. longitudinal (Taylor) dispersion
3. pendelluft
4. asymmetric velocity profiles
5. cardiogenic mixing
6. molecular diffusion

Artificial Lung Ventilation

Research at Czech Technical University, Faculty of Biomedical Engineering, and co-operating institutions

Anatomic structure of the lungs

Very complex structure of the bronchial tree is depicted on the left-hand side of the picture.
Each part of airways can be represented by a small acoustic wave-guide (more than 16 mil.), alveoli are represented as simple compliances.

Gas flow simulation

Tidal volume $V_T$

Exact Monitoring of Ventilation

Simultaneous measurement of proximal, oesophageal and intraabdominal parameters
Separate evaluation of mechanical parameters of the chest wall, lungs and the whole respiratory system
Diagnostics of ARDS type: primary (pulmonary) and secondary (extrapulmonary) forms of ARDS
Different ventilatory regimens required

Model of the respiratory system due to its anatomical structure

The model contains $67,108,859$ acoustic elements

Alveolus, alveolar pressure
**ΔP distribution**

Alveolar pressure amplitude is ± equal to the proximal one.

HFOV: Alveolar amplitude is very small.

**Total Lung Impedance (TLI)**

Different TLI dependency on R and C during CV and HFV.

Consequence: During pressure controlled ventilation:
- R causes VT changes during HFV.
- C causes VT changes during CV.

**Modelling of the respiratory system**

The model computes partial pressures of gases, airflow, and volumes along the bronchial tree using the convection-diffusion equation.

**CV vs. HFV**

- Increase in VT causes increase in alveolar oxygen fraction during HFOV.
- Hyperinflation improves oxygenation, suitable for HFOV (e.g., lung oedema).

**Assisted breathing is better in acute respiratory failure**

- Improvement of gas exchange
- Sedation ↓
- Improves cardiopulmonary function
- Ventilation days ↓ and ICU stay ↓

**Spontaneous breathing during mechanical ventilation**

- With Spontaneous Breathing
- Without Spontaneous Breathing


Putensen Curr Opin Crit Care. 2005
High-frequency oscillatory ventilation (HFOV):
- Theoretically achieves all goals of lung protective ventilation

HFOV and spontaneous breathing:
- Well (+/-) tolerated in neonatal, small patients
- Not tolerated in larger patients
  - High sedation level
  - Muscular paralysis

Why?
- HFOV = Super CPAP
- High Imposed Work of Breathing (WOB)


Imposed WOB

Physiologic WOB

Total WOB

0.3-0.6 Joules / L

Spontaneous breathing in HFOV

Demand-Flow System: 2 aims
- To assure lowest possible fluctuations in mean airway pressure
  → so that the HFOV ventilator can work
- To reduce the imposed work of breathing
  → so that the patient can breathe

Pressure in the airways
Pressure in the airways

Spontaneous breathing pressure swings around MAP generated by the patient

MAP

HFOV pressure swings around MAP generated by the oscillator

MAP

Spontaneous breathing pressure swings around MAP generated by the patient

Real pressure in the airways swings around MAP generated by the oscillator and patient

MAP

MAP

Principle of DFS

Patient

HFOV ventilator

MAP

MAP

Gas disappears from the airways (it goes into the patient’s lungs)

DFS aim: Immediate delivery of the same amount of gas into the airways as it disappears during inspiration
**Principle of DFS**

Gas disappears from the airways (it goes into the patient’s lungs)

**DFS aim:** Immediate delivery of the same amount of gas into the airways as it disappears during inspirium

**DFS aim:** “Full” compensation of the spontaneous breathing activity. The HFOV ventilator is not affected by it.

**Gas during spontaneous inspirium (or expirium) does not go through the HFOV ventilator:** It is supplied (removed) by DFS only.

**DFS very quickly reacts to the patient’s demands.**

**iWOB reduction**

Gas during spontaneous inspirium (or expirium) does not go through the HFOV ventilator. It is supplied (removed) by DFS only.

**DFS very quickly reacts to the patient’s demands.**

**Demand-flow system: Testing of its efficacy**

- **A bench study:**
  - Unloading work of breathing during high-frequency oscillatory ventilation: a bench study

- **An animal experiment:**
  - Demand flow facilitates spontaneous breathing during high-frequency oscillatory ventilation in a pig model
  - van Heerde, MD; Karri Roubik, MS, PhD; Vl Kopelent, MS, PhD; Frank B. Plötz, MD, PhD; Dick G. Markhorst, MD, PhD
  - Critical Care Med 2009 Vol. 37, No. 3

**Animal experiment**

- The animal laboratory of the Utrecht University
- 8 intubated, sedated but spontaneously breathing pigs, m = 50 kg. Lung injury was induced by repeated lung lavage with normal saline.
- Ventilation with HFOV (3100B, SensorMedics, Yorba Linda, CA) was initiated.
- A three-step protocol comprising different HFOV modes lasting 30 minutes each:
  1. HFOV and spontaneous breathing maintained with continuous fresh gas flow (e.g. using a standard ventilator without modifications).
  2. HFOV and spontaneous breathing maintained with demand flow.
  3. HFOV with suppressed spontaneous breathing.
- Pressures were sampled in the ventilator circuit, trachea and esophagus in order to calculate different components of WOB and respiratory mechanics.
- Arterial and mixed venous blood was sampled to evaluate gas exchange.
Animal experiment

Results (1): Pressure-Volume curves

Results (2): Improvement of spontaneous breathing during HFOV

<table>
<thead>
<tr>
<th>Name of parameter</th>
<th>Without the DFS</th>
<th>With the DFS</th>
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</thead>
<tbody>
<tr>
<td>Time of inspiration [sec]</td>
<td>1.25 ± 0.188</td>
<td>1.36 ± 0.197</td>
</tr>
<tr>
<td>Average rate of breath [sec]</td>
<td>0.862 ± 0.043</td>
<td>0.744 ± 0.031</td>
</tr>
<tr>
<td>Average breathing frequency [l/min]</td>
<td>21.668 ± 1.214</td>
<td>19.496 ± 1.044</td>
</tr>
<tr>
<td>Average T:V ratio [%]</td>
<td>45.100 ± 1.972</td>
<td>44.179 ± 1.618</td>
</tr>
<tr>
<td>Average tidal volume [litrer]</td>
<td>0.196 ± 0.013</td>
<td>0.296 ± 0.011</td>
</tr>
<tr>
<td>Average breathing work [J]</td>
<td>0.042 ± 0.009</td>
<td>0.021 ± 0.004</td>
</tr>
<tr>
<td>Average breathing work [J/litre]</td>
<td>0.417 ± 0.009</td>
<td>0.071 ± 0.009</td>
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Improvement of the minute ventilation by 36 %
Increase of tidal volume by 51 %
Reduction of the i-work of breathing by 83 %

Clinical Study in Adults - Study Protocol

Aim of the prospective study was to evaluate effect of HFOV in therapy of pulmonary (ARDSp) ARDS and extrapulmonary ARDS (ARDSexp) in adults.

Mean age 57 (SD 19), F/M 11/12, Pulmonary/extrapulmonary ARDS 9/14
Total CV period before HFOV: Primary 11.5 days, secondary 5.08 days

HFOV parameters:
- SensorMedics 3100B, f = 5 Hz, T1/T2 = 50%
- CDP (MAPHFOV) = 0.4 - 0.5 kPa over MAPCV
- VT = 1.5 - 2 ml/kg,
- ΔP = 50 - 100 cm H2O

Next steps:
- optimisation of CDP according to SaO2 and PaO2
- optimisation of VT according to PaCO2
- reduction of tine of persistent hypercapnia

After stabilisation:
- V2 monitoring in order to maintain it constant, Rint monitoring

Weaning:
- stepwise reduction of CDP (without effect on PaO2), if CDP < 1.8 kPa then switch to conventional ventilation

Oxygen gain 1:
difference between average value of PaO2/FiO2HFOV and PaO2/FiO2CV

Oxygen gain 2:
difference between peak value of PaO2/FiO2HFOV and PaO2/FiO2CV

Optimal CDP

ΔP represents a difference between optimal CDPHFOV and optimal MAPCV
Conclusions from the HFOV clinical study

- Improvement of hypoxemic index is statistically significant ($p<0.001$) in ARDSexp. There is no significant oxygenation improvement in ARDSP.

  The effect of HFOV could be connected to different aetiology of pulmonary tissue impairment and also to parameters of ventilatory mechanics of the chest wall / lungs in mentioned forms of ARDS.

Technical support of research

- Design and construction of ventilatory equipment for both conventional and unconventional ventilation.

Why HFOV ‘fails’ in RCTs?

HFOV is not understood yet, therefore:

No evidence-based recommendations how to use HFOV (e.g. No data exists to predict the optimal frequency or inspiratory time to control arterial carbon dioxide in adults; frequencies of 4 – 6 Hz have no scientific basis and are purely empirical.)

No exact definition of ventilatory parameters (e.g. ΔP is set to achieve adequate chest wall "wiggle", or ΔP is initially set to achieve chest wall vibration to the level of mid-thigh; tidal volume is not measured at all, etc.)

Heterogeneity of the study groups (different adjunct therapies, possibility of spontaneous breathing, etc.).

Conclusion

Artificial lung ventilation is non-physiological and can damage the lungs.

HFOV offers a ventilatory strategy which may be both protective and efficient in ARDS patients.

We should be very careful so that we do not overestimate and/or underestimate its advantages and disadvantages.

... to get to know HFOV properly and to study artificial lung ventilation.