What is an Optimal Paw Strategy?

A Physiological Rationale

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Acute injury sequence

Barotrauma
Volutrauma
Atelectotrauma
Biotrauma
Oxidative Toxicity
Fluid, blood, protein leakage and impaired mechanics

Lung injury is a multi-factorsial event of conflicting aetiologies
Lung Protective Strategies

- Lung Protective Mechanical Ventilation Strategies aim to:
- Achieve optimal gas exchange
  - Recruit collapsed alveoli uniformly
  - Minimise the known causes of VILI:
    - Atelectasis
    - Volutrauma
    - Sheer-force stresses
    - Oxidative Injury
    - Rheotrauma
Small $V_T$, PEEP and LPV

Optimal ventilation strategy - systematic review

18 trials (n=3229 infants)

• Subgroup analysis revealed it was more important how ventilation was delivered, rather than modality of ventilation:
  – Low lung volume strategies: worse outcomes
  – High lung volume strategies: small but significant reduction in death or CLD
Effect of a single sustained inflation on lung volume and oxygenation during HFOV

Kolton et al
- During HFOV, a static inflation (SI) improved lung volume

Hamilton et al 1983
- During ventilation, a static inflation improved oxygenation in HFOV group

Key:
- a - disconnection
- b - PEEP
- c - HFOV
- d - static inflation
- e - HFOV at initial Paw

High Lung Volume and Oxygenation

Exploiting Hysteresis to achieve the desired lung volume

The Pressure-Volume Relationship

Hysteresis

Volume

Pressure
Targeting Ventilation on the PV Relationship

- 2 injury zones during mechanical ventilation
  - **Low Lung Volume**
    Ventilation tears adhesive surfaces
  - **High Lung Volume**
    Ventilation over-distends, → Volutrauma
- Need to find the “Sweet Spot”

Mapping the PV Relationship using an open lung ventilation strategy

- [Image: Diagram showing various lung volumes and pressures]
  - [Label] LIP, UIP, CCP, OPT, TLC
  - [Label] MAP cmH₂O

- [Citation] Dargaville et al. ICM, 2010
Ventilation along the inflation limb

- Amato et al proposed ventilation along the inflation limb between LCP and UCP
- At alveolar level:
  - Gains in lung volume may be either by recruitment of alveoli, or overdistension of already recruited lung units
  - Relative proportion of each varies along the inflation limb
- Affected by continued recruitment along the whole limb
- At no point along the inflation limb can all mechanical causes of VILI be minimised
  - Hickling et al Am J Respir Crit Care Med 2001
  - Jonson Intensive Care Med 2005

Ventilation along the inflation limb

Zero PEEP

- Halter et al Am J Respir Crit Care Med 2005
Ventilation along the deflation limb

• Affected by alveolar collapse only at pressures below the critical closing pressure
  □ Halter et al. *Am J Respir Crit Care Med* 2003

• Volume loss likely a combination of decreasing alveolar dimensions and derecruitment of lung units
• Pressure required to open lung units exceeds that required to prevent collapse once opened
  □ Rimensberger *Intensive Care Med* 2000

• Alveolar stability can be maintained during expiration along the deflation limb
  □ Albaiceta *Crit Care Med* 2004

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Ventilation along the deflation limb

Post recruitment PEEP 5 cmH₂O
Post recruitment PEEP 10 cmH₂O

□ Halter et al. *Am J Respir Crit Care Med* 2003
Achieving Ventilation on the Deflation Limb

Alveolar Recruitment Techniques

Sustained inflations during HFOV

• Bond et al:
  – HFOV with SI vs HFOV alone
  – SI of 30 cm H$_2$O for 15 s
  – higher oxygenation target in the SI
  group achieved at the same $P_{aw}$
    ☐ Crit Care Med 1993

• Walsh et al:
  – systematic examination of magnitude and duration of SI
  – SI of 5 cm H$_2$O > $P_{aw}$ or for 3 s were ineffective at improving oxygenation
  – SI of 10 cm H$_2$O > $P_{aw}$ for 10 s always effective
    ☐ J Appl Physiol 1988
Sustained inflations during HFOV

• Byford et al (1988)
  – comparison of static and dynamic inflations during HFOV
  – both effective at improving oxygenation and increasing lung volume
  – an equivalent improvement in oxygenation or lung volume could be achieved at a $P_{aw}$ 5 cm H$_2$O lower if a dynamic inflation was used

\[\square J\text{ App}l\text{ Physiol}\ 1988\]

Comparison of Alveolar Recruitment Strategies

\[\text{□ Pellicano et al JCM 2009}\]
Comparison of Alveolar Recruitment Strategies: Lung Volume

*P = 0.04 ANOVA

Pellicano et al. ICM 2009

Comparison of Alveolar Recruitment Strategies: Oxygenation

Pellicano et al. ICM 2009
Comparison of Alveolar Recruitment Strategies: End Lung Volume

Comparison of Recruitment Strategies: Homogeneity of lung Volume

Pellicano et al. ICM 2009
The Open Lung Approach To Lung Protection

Open Lung Ventilation

“open the lung, find the closing pressure, re-open it and keep it open!”

Ventilation applied with an *Open Lung Concept*:
1. Improves Gas exchange
2. Reduces VILI & protein leakage
3. Preserves surfactant function
4. Attenuates lung mechanics
5. PPV comparable to HFOV

Small VT PPV (5ml/kg) and HFOV applied at 50% of TLC (after SI)

Rimensberger *et al* Crit Care Med 1999
Rimensberger *et al* Intensive Care Med 2000
Open Lung Ventilation
Short-term outcome

van Kaam et al, Crit Care Med 2004

Open Lung Ventilation
Lung injury outcome

van Kaam, Ped Research, 2003
Open Lung Ventilation

Lung volume changes during recruitment

Pressure/oxygenation curve

Pressure/impedance curve

n=15 GA=28.7 wk BW=970 g

Tingay et al. Am J Respir Crit Care Med, 2006

Miedema et al. J of Pediatr 2011
PV relationship influences lung mechanics

Optimum ventilation strategy

- Recruits atelectatic lung units
- Maintains ventilation at or near the deflation limb with pressures above the critical closing pressure and uses the smallest possible amplitudes to effect CO2 removal
- Is titrated against degree of lung disease, recruitment potential and hysteresis of the lung
- Is frequently reassessed in response to changes in lung mechanics
Time Dependence of Lung Recruitment

Kolton et al:  
- Showed time dependent recruitment in both HFOV and CMV groups  
[Anesth Analg 1982]

Key:  
a = disconnection  
b = PEEP  
c = HFOV/CMV  
d = static inflation  
e = HFOV/CMV at initial P_{aw}
Time Dependence

Pellicano et al ICM 2009

Time dependence during HFV in nRDS

Stabilization time

Thome et al. AJRCCM 1998

n=13
GA=26 wk
BW=790 g
Age= 4 days
High-frequency ventilation
Stabilization time after recruitment steps

- Dependent on lung condition (surfactant)
- Dependent on distribution of disease
- In early (homogeneous) RDS wait at least 2 minutes and longer depending on response
- In older (heterogeneous) lung disease longer stabilization times (upto 1 hour) are needed

Conclusions
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• High lung volumes are necessary during HFOV
• Lung volume at a given $P_{aw}$ varies considerably, due to hysteresis
• Using hysteresis it is possible to ventilate the lung at different points within the pressure-volume relationship, depending on the pressure strategy applied
• By applying ventilation on the deflation limb, higher lung volumes and better oxygenation can be achieved at a lower $P_{aw}$

Conclusions

• Alveolar recruitment strategies may be used upon initiation of HFOV to achieve ventilation near the deflation limb
• Use stepwise lung recruitment with a stabilization time between 2 – 60 minutes depending on underlying lung disease