HFOV IN PRACTICE: The recruitable lung

David Tingay

Preterm Infant

- 28/40 GA
- BW 1 kg
- Intubated at 1 hr
- P_{aw} 12 cm H2O
- FiO2 1.0
- SpO2 86%
- PaO2 45 mmHg
- PaCO2 55 mmHg

HFOV Settings?

- P_{aw} 14
- FiO2 0.8
- SpO2 90%
- PaO2 52 mmHg
- PaCO2 53 mmHg

Pre-HFOV Questions

- Device?
- Monitoring
- Positioning
- Sedation/Analgesia/MR
- Cardiac Support
- PPHN
- Biochemical support
## HFOV vs CMV: High Lung Volume Strategy

![Diagram showing comparison between HFOV and CMV]

Cools (PreVILI Group) Lancet

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**Lung-protective ventilation strategies in neonatology: What do we know—What do we need to know?**

Anthony H. van Baaren, MD, PhD, Peter C. Rimensberger, MD

<table>
<thead>
<tr>
<th>Author</th>
<th>Methods</th>
<th>HFOV (Y/N)</th>
<th>Targets</th>
<th>Paw (cm H(_2)O)</th>
<th>Poi*</th>
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<tbody>
<tr>
<td>Höffel et al. (4)</td>
<td>N</td>
<td>—</td>
<td>—</td>
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<td>Carlo et al. (5)</td>
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<td>Mouret et al. (12)</td>
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<td>—</td>
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<td>8–9</td>
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<td>Beesling et al. (16)</td>
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<td>—</td>
<td>—</td>
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<tr>
<td>Tzillo et al. (17)</td>
<td>Y</td>
<td>≥0.25</td>
<td>—</td>
<td>13</td>
<td>0.20</td>
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</tbody>
</table>

HFS: high-volume strategy as indicated by the intention to optimize lung volume during HFOV; Y/N, yes/no; Paw, mean airway pressure; CSR, number of ribs indicating optimal lung inflation; CMV, conventional mechanical ventilation; —, data not provided.

Data several hours after surfactant therapy unless stated differently: number of ribs indicating optimal lung inflation; no explicit data provided; *Poi* before surfactant; after surfactant, PiO\(_2\) decreased to 0.39–0.55; *Poi* before surfactant.
High lung volume strategy (HLVS)
Traditional definition

Cochrane database definition (at least 2 of):
1. Initial use of a higher mean airway pressure than on CMV
2. Initial weaning of fractional inspired oxygen before mean airway pressure
3. Use of alveolar recruitment manoeuvres

Initiating HFOV
Preterm Infant

- 28/40 GA
- BW 1 kg
- Intubated at 1 hr
- $P_{aw}$ 12 cmH₂O
- $FiO₂$ 1.0
- $SpO₂$ 86%
- $PaCO₂$ 45 mmHg
- $PaCO₂$ 55 mmHg

HFOV Settings?

- $P_{aw}$ 14
- $FiO₂$ 0.8
- $SpO₂$ 90%
- $PaO₂$ 52 mmHg
- $PaCO₂$ 53 mmHg
‘Static’ $P_{aw}$ HLVS

How do you know you are in the Safe Window?

$P_{OPT}$

The Open Lung Concept

Lachmann ICM 1990

‘open the lung, find the closing pressure, re-open it and keep it open!’

- Achieve Lung Recruitment
- Identify the lowest pressure that maintains that recruitment (OPTIMAL PRESSURE; $P_{OPT}$)
- Exploit the hysteresis of the lung
- Exploit PEEP – an expiratory phenomenon that maintains recruitment
**Relationship between $P_{AW}$ and EELV**

**Term Infants**

![Graph showing relationship between $P_{AW}$ and EELV for term infants.]

**Preterm Infants**

![Graph showing relationship between $P_{AW}$ and EELV for preterm infants.]

- Tingay et al AJRCCM 2006
- Miedema et al J Peds 2011

PV relationship can be mapped at the bedside with $P_{AW}$

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**Initiating HFOV**

**Preterm Infant**

- $P_{aw}$ 14
- $P_{aw}$ 20
- $P_{aw}$ 21
- $P_{aw}$ 18
- $P_{aw}$ 16

- $FiO_2$ 0.8
- $SpO_2$ 90%
- $PaO_2$ 52 mmHg
- $PaCO_2$ 55 mmHg
- $PaCO_2$ 60 mmHg

- $FiO_2$ 0.5
- $SpO_2$ 88%
- $PaO_2$ 60 mmHg
- $PaCO_2$ 70 mmHg

- $FiO_2$ 0.6
- $SpO_2$ 93%
- $PaO_2$ 60 mmHg
- $PaCO_2$ 60 mmHg

- $FiO_2$ 0.7
- $SpO_2$ 95%
**Region of Optimal Ventilation?**

**Deflation Limb**
- Alveolar stability maintained
- Albaiceta
  - CCM 2004
- Opening pressure > collapsing forces
  - Remensberger
  - ICM 2000

**Inflation Limb**
- Recruitment is ongoing (inhomogeneity)
- At no point can all mechanical causes of VILI be minimised
  - Hickling et al
  - AJRCCM 2001
  - Jonson
  - ICM 2005

HFOV is most lung protective in animal models when alveolar re-expansion is achieved with a volume recruitment manoeuvre and then maintained with an appropriate $P_{aw}$.

**Froese AJRCCM 2002**

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**Initiating HFOV**

**Preterm Infant**

<table>
<thead>
<tr>
<th>$P_{aw}$ (cm H$_2$O)</th>
<th>$P_{open}$</th>
<th>$P_{aw}$</th>
<th>$P_{aw}$</th>
<th>$P_{aw}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14</td>
<td>20</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>$P_{aw}$</td>
<td>14</td>
<td>20</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>$FiO_2$</td>
<td>0.8</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>$SpO_2$</td>
<td>90%</td>
<td>93%</td>
<td>96%</td>
<td>95%</td>
</tr>
<tr>
<td>$PaO_2$</td>
<td>52 mmHg</td>
<td>65 mmHg</td>
<td>60 mmHg</td>
<td>60 mmHg</td>
</tr>
<tr>
<td>$PaCO_2$</td>
<td>53 mmHg</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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14/04/15
Relationship between \( P_{AW} \), Lung Volume and \( \text{SpO}_2 \)

- \( \text{SpO}_2 \) reliably identified TLC (overdistension) and CCP (collapse)
- \( \text{SpO}_2 \) cannot precisely delineate between small volume state changes

Initiating HFOV

Preterm Infant

\[ P_{\text{open}} \]
\[ P_{\text{aw}} = 20 \]
\( \text{FiO}_2 = 0.5 \)
\( \text{SpO}_2 = 93\% \)
\( \text{PaO}_2 = 80 \text{ mmHg} \)

\[ P_{\text{initial}} \]
\[ P_{\text{aw}} = 14 \]
\( \text{FiO}_2 = 0.8 \)
\( \text{SpO}_2 = 90\% \)
\( \text{PaO}_2 = 52 \text{ mmHg} \)
\( \text{PaCO}_2 = 53 \text{ mmHg} \)

\[ P_{\text{opt}} \]
\[ P_{\text{aw}} = 11 \]
\( \text{FiO}_2 = 0.6 \)
\( \text{SpO}_2 = 84\% \)
\( \text{PaO}_2 = 49 \text{ mmHg} \)

\[ P_{\text{close}} \]
\[ P_{\text{aw}} = 8 \]
\( \text{FiO}_2 = 0.6 \)
\( \text{SpO}_2 = 84\% \)
\( \text{PaO}_2 = 52 \text{ mmHg} \)
\( \text{PaCO}_2 = 49 \text{ mmHg} \)

\[ P_{\text{final}} \]
\[ P_{\text{aw}} = 20 \]
\( \text{FiO}_2 = 0.4 \)
\( \text{SpO}_2 = 95\% \)

\( \text{PaO}_2 = 52 \text{ mmHg} \)
\( \text{PaCO}_2 = 41 \text{ mmHg} \)
OLV during HFOV in newborn infants

Rimensberger et al Pediatrics 1999

- LVO (if \( F_{I02} > 0.4 \)): 1-2 cm H₂O \( P_{aw} \) steps every 1-2 mins UNTIL \( F_{I02} \leq 0.4 \) (max \( P_{aw} \) 25 cm H₂O)
- THEN \( P_{aw} \) decreased until \( F_{I02} \leq 0.4 \) and \( P_{aO2} \geq 60 \) mmHg

Less ventilator days, Lower oxygen dependency, Less CLD

Transient high \( P_{aw} \) is well tolerated, even in preterm infants

Delaege et al AJRCCM 2006

Similar LVO strategy:

- \( P_{max} F_{I02} \) at CDP\(_{OPT} \) \( \leq 0.25 \) before surfactant
- \( F_{I02} \) at CDP\(_{OPT} \) \( \leq 0.25 \) in 75% and \( \leq 0.3 \) in 98%

An aggressive recruitment strategy using oxygenation to guide the recruitment process is feasible and safe during HFV in preterm infants with RDS.

Tingay et al AJRCCM 2006

OLV resulted in optimal \( SpO_2, TcCO_2, V_1 \) and \( C_1 \).
Optimal \( P_{aw} \) identified after aggressive recruitment at CCP+2 – 4 cm H₂O

The Amsterdam experience

n = 103

\( F_{I02} \) at CDP\(_{OPT} \) \( \leq 0.25 \) in 75% and \( \leq 0.3 \) in 98%

\( TcCO_2 \) was reduced by 9 mmHg after optimal recruitment (pre-surfactant)

An open lung ventilation strategy using oxygenation to guide the recruitment process is feasible and safe during HFV in preterm infants with RDS.
Initiating HFOV
Preterm Infant

$P_{\text{aw}}$ 14
FiO$_2$ 0.8
SpO$_2$ 90%
PaCO$_2$ 52 mmHg
PaCO$_2$ 53 mmHg

$P_{\text{aw}}$ 8
FiO$_2$ 0.6
SpO$_2$ 84%
PaCO$_2$ 49 mmHg

$P_{\text{aw}}$ 20
FiO$_2$ 0.4
SpO$_2$ 95%
PaCO$_2$ 60 mmHg

$P_{\text{aw}}$ 11
FiO$_2$ 0.4
SpO$_2$ 92%
PaCO$_2$ 41 mmHg

PV relationship influences lung mechanics

↑ $C_{RS}$ + ↓ deadspace
= PCO$_2$ lower

Overdistension → $C_{RS}$ low
+ ↑ dead space = PCO$_2$ high

↑ $C_{RS}$ = PCO$_2$ lower

Atelectasis → $C_{RS}$ low = PCO$_2$ high

J Clin Invest 1959. 38:2168
Is Oxygenation the best marker of the optimal EEV?

Zannin Ped Res 2014

PV relationship influences lung mechanics

Miedema et al. ERJ 2012

Tingay et al CCM 2013
The Optimal Safe Window

The region of the Deflation Limb > $P_{close}$ that balances optimal oxygenation and lung mechanics.

Tingay et al CCM 2013

Effect of Lung Recruitment on Pulmonary, Systemic, and Ductal Blood Flow in Preterm Infants

Smolich et al 2014 PSANZ (Preterm Lambs)
How long until EEV stabilises after a $P_{aw}$ change?

**Preterm infants**

<table>
<thead>
<tr>
<th></th>
<th>Global t (s)</th>
<th>Ventral t (s)</th>
<th>Dorsal t (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation limb before surfactant (n = 95)</td>
<td>27.3 (12.5 – 53.9)</td>
<td>28.5 (12.8 – 62.7)</td>
<td>23.0 (8.9 – 37.7)*</td>
</tr>
<tr>
<td>Deflation limb before surfactant (n = 89)</td>
<td>16.1 (7.8 – 30.6)*</td>
<td>16.3 (7.3 – 29.3)*</td>
<td>18.7 (8.8 – 44.5)*</td>
</tr>
<tr>
<td>Deflation limb after surfactant (n = 24)</td>
<td>44.3 (30.1 – 70.8)*</td>
<td>40.3 (22.5 – 64.5)*</td>
<td>61.2 (30.5 – 81.5)*</td>
</tr>
</tbody>
</table>

**Term infants**

**Definition of abbreviations:**
- $P_{aw}$ = closing pressure
- $P_{op}$ = opening pressure
- $t$ = time constant

* indicates a significant change compared to the ventral $t$, $p < 0.01$.

Miedema et al ICM 2012
But, I must give surfactant!
Optimum point of ventilation may change

- N=15 preterm infants
- EIT measurements during OLV before and after surfactant administration
- Surfactant administration:
  - Increased EELV by 61±39%
  - Improved distribution of ventilation:
    - V:D ratio 1.16 vs 0.81
  - Lowered the CCP:
    - 16.4±3.1 vs 10.4±2.4 cm H₂O

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Setting the Frequency - Considerations

- Frequency influences the stroke volume
- The time constant of the lung determines frequency
- Lung disease and size determines time constant
- BUT there are risks of going too high and too low in the RDS lung
- Compliant lungs - marked damping of HFOV pressure
- Potential for barotrauma in the poorly recruited lung at low frequency
**Setting the Frequency – Practical guide**

**Suggested initial maximum frequency settings**

- **PIE in evolution**
  - Preterm HMD
  - Preterm HMD (Dräger BL+VN)*
  - Meconium aspiration syndrome
- **Term lung disease**
  - *Established PIE with high FiO₂ and CO₂ retention**
  - Term lung disease

**Weaning to extubation**

<table>
<thead>
<tr>
<th>Options:</th>
<th>Preterm</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wean to low $P_{AW}$ and extubate directly from HFOV</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Wean to low $P_{AW}$, brief period of low rate SiMV (or ETCPAP), then extubate</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>When lung disease improved transfer to synchronized IMV and extubate when able</td>
<td>√</td>
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</tbody>
</table>
At what HFOV settings can we extubate?

**Preterm**

- FiO\(_2\) < 0.3
- \(P_{AW}\) 6-8 cm H\(_2\)O
- \(\Delta P\) 10-15 cm H\(_2\)O
- WOB satisfactory
- pH > 7.25

**Term**

- FiO\(_2\) < 0.3
- \(P_{AW}\) 6-10 cm H\(_2\)O
- \(\Delta P\) 15-20 cm H\(_2\)O
- WOB satisfactory
- pH > 7.25

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van Velzen A et al. *PCCM* 2009

- 214 preterm infants (29.5 ± 2.5 wk, BW 1300 ± 480 g)
- Early OLV HFOV
- Extubation from HFOV attempted at a median age of 62 hrs
- Successful in 193 (90%) of the infants.
- \(P_{AW}\) at the time of extubation 6.8 ± 1.6 cmH\(_2\)O
Summary

- In the atelectatic lung, lung recruitment can be individualised using an open lung strategy
- Watch your patient, use the clues available and adapt

EEV
SpO₂
Mechanics

Too Little
Too Much

‘From Art to Science’

Old and new concepts in the application of high frequency oscillatory ventilation

Day 2
Session 2: Putting HFOV into clinical practice

HFOV in practice – the recruitable lung
David Tingay/Andreas Schibler

HFOV in the non-recruitable lung
Peter Dargaville
Pressure cost of ventilation

Peak alveolar distension

\[ D_{alv} = \left( V_{EE} + V_T \right) / TLC \]

\[ D_{alv} \]

Shaded regions = 'safe' Paw & Fr options
(Peak \( D_{alv} < 90\% \) TLC)

RDS = less room for error in choice of Paw and Fr

Venegas J & Fredberg J, Crit Care Med, 1994

Hysteresis

For any given Pressure there is a range of volumes that can exist

Thus, for any given Volume there is a range of pressures that can achieve it

That pressure will always be lower on the deflation limb, because \( P_{cl} < P_{op} \)

Crotti et al AJRCCM 2001

Gattinoni et al AJRCCM 2001