Background

The injured lung (ALI / ARDS) is susceptible to iatrogenic injury as a result of mechanical ventilation (ventilator induced lung injury, VILI).

Lung over-inflation as a result of excess pressure (barotrauma) or volume (volutrauma); repetitive alveolar collapse and recruitment (atelectotrauma); and stimulation of the inflammatory response resulting from lung injury giving rise to further cytokine-mediated lung and distant organ injury (biotrauma) are all thought to contribute to VILI.

Lung protective ventilator strategies are based upon the following principles:

− Use low tidal volume to limit lung stretch.
  − ARDSNet study used 6 mL/kg predicted body weight.
− Attain and maintain lung recruitment to prevent atelectotrauma, which may occur even if using low tidal volumes. Use lung recruitment manoeuvres and PEEP.
− Limit plateau pressure to < 32 cmH2O.

Adjunctive strategies:

− Permissive hypercapnoea (consequence of low tidal volume and rate used in order to limit frequency and degree of lung stretch).
− Prone ventilation to recruit lung and improve distribution of ventilation (may also improve removal of secretions).
− Nitric oxide to improve oxygenation and reduce vascular stress.
− Positioning - lateral rotation therapy

HFOV produces very small tidal volumes (less than anatomical dead space) and achieves CO2 clearance without the large cyclical pressure changes required in conventional ventilation. HFOV is able to maintain relatively high mean airway pressure (mPaw) (and thus increase lung volume and oxygenation) without the risk of cyclical lung overdistension. HFOV has been shown to provide adequate ventilation and oxygenation in ARDS patients and shows promise as a means of applying lung-protective ventilation in patients where conventional ventilation is failing (1,2)

Principle of operation

The SensorMedics 3100B HFOV produces a pressurised patient circuit (best characterised by the mean airway pressure) by passage of a continuous flow of gas (bias flow) and a control valve. The gas in the patient circuit is oscillated by means of an electrically driven diaphragm. The frequency of oscillation can be varied between 3 and 15 cycles per second (Hertz, Hz). The amplitude of forwards and backwards displacement of the diaphragm from the resting position can be varied. The amount of diaphragm
displacement, the speed of displacement, and characteristics of the circuit, airway and respiratory system compliance determine the pressure swing around the mean airway pressure (the delta pressure, \( \Delta P \)). Even though the \( \Delta P \) is high, pressure transmission beyond the endotracheal tube (ETT) is greatly attenuated. Pressure attenuation is determined by ETT diameter, oscillator frequency, airway resistance and respiratory system compliance. The degree of chest “wiggle” seems to be related to the degree of pressure transmission ie. more pressure transmission = more “wiggle”. The tidal volumes produced are less than dead space volume and are determined by \( \Delta P \), frequency, airways resistance (mainly from the ETT), and respiratory system compliance. FiO2 and mPaw determine oxygenation (3).

Mechanisms of CO2 transport (4)

CO2 transport in HFOV is complex and depends upon the following mechanisms:

- Convection - bulk movement of gas in proximal gas exchange units.
- Convection and diffusion resulting from:
  - Turbulence, asymmetric gas velocity profiles resulting in radial mixing of fresh inspired and expired gas.
  - Time constant inequalities and phase differences between lung units (differences in regional resistance and compliance) resulting in convective transport.
  - Oscillations resulting from cardiac contraction contribute to gas mixing.
  - Diffusion (Brownian motion) in distal gas exchange units.

Effect of frequency and tidal volume on ventilation (4)

Tidal volume has a greater effect on ventilation than frequency. However tidal volume is dependent upon the pressure amplitude transmitted to the lung, with increased \( \Delta P \) resulting in greater pressure transmission and thus tidal volume. Pressure amplitude transmitted to the lung is reduced with increasing frequency. To maximise lung protection emphasis is place upon achieving as high as possible frequency in combination with the lowest \( \Delta P \).

For any given setting of \( \Delta P \), frequency, or mPaw the pressure transmitted to the lung is dependent upon the mechanical properties of the endotracheal tube, airways, lung and chest wall.

Mechanical factors influencing pressure transmission (4, 5)

- As impedance increases higher \( \Delta P \) is required to maintain flow / volume delivery to gas exchange units.
- Impedance is dependent upon elastance, resistance and inertance of the ventilator, ETT and respiratory system. Inertance describes rate of change in gas flow and respiratory system volume for a given pressure change. Although relatively unimportant in convention ventilation inertance become significant at the high frequencies used in HFOV.
Factors affecting impedance

The lung behaves as an overdamped system - with increased frequency there is increased attenuation of pressure amplitude.

The natural frequency of adult ARDS lung has been estimated to be 8.6 Hz and a corner frequency (the frequency at which the response falls off) of about 3.2 Hz. These values correspond to the frequencies used in clinical practice (ie > 3 Hz). These values will be changed by relative changes in inertance and resistance ie. increasing resistance shifts the corner frequency to lower values.

− There will be increased pressure transmission to the alveoli with decreased compliance.
− Increasing airway resistance will reduce the pressure transmission to the alveoli but increase the pressure amplitude in the trachea.

Tracheal tube

The ETT contributes > 50% of total impedance and about 90% of inertance.

Patient Selection / Starting Criteria (6, 7)

A trial of HFOV will be considered if a patient fulfils the criteria for ARDS;

− Diffuse bilateral infiltrates
− No clinical evidence of left ventricular failure
− PaO₂ to FiO₂ ratio < 200 mmHg

Plus

− Intubated and on conventional mechanical ventilation for 48 hours and;
  FiO₂ is > 0.6 and unable to maintain PaO₂ > 65mmHg (PEEP at least 15 cmH₂O)

*If bronchoscopy or CT scan is required it should be done before initiation of HFOV.*
Goals of therapy

**Ventilation:** To maintain arterial pH in the range 7.20 to 7.35.

In order to limit the need for increased ventilation consider administration of NaHCO₃ to accelerate metabolic compensation for respiratory acidosis if pH < 7.2 (pH will be < 7.2 if the PaCO₂ > 70 mmHg and the SBE is in the normal range).

Administer 100 mmol (100 mL of 8.4% NaHCO₃) over 2 to 4 hours and reassess.

The increase in strong ion difference (SID = Na⁺ + K⁺ – Cl⁻) (by the addition of Na⁺ without Cl⁻ (ie. NaHCO₃)) required for complete compensation can be estimated from the relationship for chronic respiratory acidosis ie. \(\Delta SBE = 0.4 \times \Delta PaCO₂\). (8)

Therefore the required increase in SID is estimated by 0.4 × increase in PaCO₂ (actual PaCO₂ – normal PaCO₂) = 0.4 × (PaCO₂ – 40) mEq/L

\[Na⁺ \text{ required} = (\text{Body weight} \times 0.6 \text{ (distribution volume for Na⁺}) \times \text{required increase in SID}) \text{ mmol/L}\]

**Oxygenation:** PaO₂ 55 – 80 mmHg or SpO₂ 88 – 95% (defer to PaO₂ target if only one is out of range)
**Table 1. Adjusting settings (from references 6 and 7)**

<table>
<thead>
<tr>
<th>Ventilation</th>
<th>Oxygenation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overall;</strong> aim for highest frequency and lowest (\Delta P)</td>
<td><strong>Overall;</strong> aim for mPaw (\leq 30) cmH(_2)O, FiO(_2) (\leq 60%)</td>
</tr>
</tbody>
</table>
| **Initial settings;** | **Initial settings;** mPaw = mPaw on conventional ventilation + 5 cmH\(_2\)O but not exceeding 35 cmH\(_2\)O  
FiO\(_2\) = 1.0 |
| \(\Delta P = 60\) cmH\(_2\)O  
**Frequency** = 6 Hz  
If PaCO\(_2\) > 60 mmHg on conventional ventilation use;  
\(\Delta P = 70\) cmH\(_2\)O  
**Frequency** = 5 Hz | Perform cycle of up to 3 RM\(\text{s} at commencement of HFOV – see note on RM for details.** |
| **Adjustments:** | **Adjustments:** |
| **pH in target range –** | **If oxygenation below target** – increase mPaw by 5 cmH\(_2\)O steps (max of 45 cmH\(_2\)O) – consider recruitment manoeuvre (RM). |
| (a) increase frequency by 1 to 2 Hz to max of 12 Hz | **If oxygenation is improving:**  
(a) Reduce FiO\(_2\) in 0.1 steps till FiO\(_2\) < 0.6.  
(b) Decrease mPaw in 5 cmH\(_2\)O steps to minimum of 20 cmH\(_2\)O.  
Allow 30 mins between steps for worsening oxygenation.  
Allow 4 hours between steps for improving oxygenation.  
Use SpO\(_2\) and ABGs to guide.  
RM (see note on RM) if SpO\(_2\) decreases \(> 5\%\) with;  
– Suctioning  
– Bronchoscopy  
– Circuit disconnection |
| **pH is too high** – (correct metabolic alkalosis if indicated) |  
(a) increase frequency by 1 to 2 Hz to max of 12 Hz.  
(b) decrease \(\Delta P\) in 5 cmH\(_2\)O steps to minimum of 20. |
| (a) increased \(\Delta P\) in steps of 5 cmH\(_2\)O to max of 90 cmH\(_2\)O then;  
(b) add cuff leak (see note below).  
(c) decrease frequency in 1 Hz steps to min of 3 Hz. |  
Consider inhaled nitric oxide and/or prone position.  
Return to conventional ventilation. |
| **pH is too low** – (correct metabolic acidosis if indicated). |  
consider altered disease process: possibility of pneumothorax, partial ETT obstruction, brochospasm, de-recruitment).  
| (a) increased \(\Delta P\) in steps of 5 cmH\(_2\)O to max of 90 cmH\(_2\)O then;  
(b) add cuff leak (see note below).  
(c) decrease frequency in 1 Hz steps to min of 3 Hz.  
Allow 30 minutes between changes – use ABGs to guide. |  
Consider inhaled nitric oxide and/or prone position.  
Return to conventional ventilation. |
| **Failure of HFOV** |  
Increased PaCO\(_2\) with pH < 7.2 despite maximum \(\Delta P\), frequency of 3 Hz, and cuff leak. (ensure ETT patency). |
Setting cuff leak - reduce cuff pressure until mPaw falls by 5 cmH₂O. Increase bias flow to re-establish original mPaw.

Consider size 6 ETT tube placed in hypopharynx if upper airway oedema (swelling, burns) to help gas escape.

Recruitment manoeuvres

To be conducted only after assessment of adequacy of cardiovascular function and volume status. ICU Consultant or Registrar must be in attendance during procedure.

- Cycle of up to 3 RM s at commencement of HFOV
- RM if SpO₂ decreases ≥ 5% with;
  - Suctioning
  - Bronchoscopy
  - Circuit disconnection

Procedure.

Set high airway pressure alarm to 50 cmH₂O
Inflate cuff to occlude leak
Set HFOV to standby
Increase mPaw to 40 – 45 cmH₂O for 40 – 60 secs (watch BP and decrease mPaw immediately if MAP < 60 mmHg or fall more than 20 mmHg)

Return mPaw to previous setting
Reset cuff leak
Restart piston

Recruitment manoeuvres algorithm at commencement of HFOV (from reference 10)

**Step 1**
RM: FiO₂ = 1.0, ΔP = 0
mPaw = 45 cmH₂O for 40 – 60 secs
Begin Oscillation

**FiO₂ ≥ 0.6 ?**
Repeat RM up to max of 3 cycles
Consider further RM s 2 to 3 X per 24 hrs if FiO₂ > 0.4

**FiO₂ < 0.6 ?**
Wean mPaw

**Step 2**
Measure ABGs 10 mins after RM
Adjust ΔP and frequency
Wean FiO₂ in 0.1 steps every 2 minutes.
Stop when: FiO₂ = 0.4 or SpO₂ = 88 – 95%
Assessment

− Note mPaw on conventional ventilation.
− Obtain ABG prior to and 15 mins post commencement of HFOV.
− ABGs half hourly for the first 2 hours of HFOV and then 4th hourly / prn.
− Assess for hyperinflation – anterior 6th rib visible above the diaphragm.

Observations

− Set mPaw alarm at mPaw +/- 5 cmH2O.
  Hourly;
  − mPaw,
  − amplitude,
  − Inspired %,
  − Frequency,
  − Bias flow,
  − SpO2,
  − power setting
  − humidifier water level

Changes in observations

− Increase in ∆P for same power setting may indicate;
  − Increased ETT resistance (eg, kink, partial blockage, misplacement).
  − Bronchospasm

− Spontaneous breathing will cause mPaw and ∆P fluctuations
− Changes in lung compliance will cause changes in ∆P

Table 2. Affects of clinical situations on ∆P and tidal volume (6)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Vt</th>
<th>∆P&lt;sub&gt;carinal&lt;/sub&gt;</th>
<th>∆P&lt;sub&gt;proximal&lt;/sub&gt;</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alveolar overdistention</td>
<td>▼</td>
<td>▲</td>
<td>▼</td>
<td>Decrease mPaw incrementally</td>
</tr>
<tr>
<td>Tension pneumothorax</td>
<td>▼</td>
<td>▲</td>
<td>▼</td>
<td>Decrease mPaw. ? chest tube</td>
</tr>
<tr>
<td>Mucous plugging</td>
<td>▼</td>
<td>▲</td>
<td>▼</td>
<td>Bag, saline lavage and suction. ? bronchoscopy</td>
</tr>
<tr>
<td>Bronchoconstriction</td>
<td>▼</td>
<td>▲</td>
<td>▼</td>
<td>Bronchodilators / steroids</td>
</tr>
<tr>
<td>Acute pulmonary oedema</td>
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<td>▼</td>
<td>▲</td>
<td>Increase mPaw</td>
</tr>
<tr>
<td>Partial ETT obstruction</td>
<td>▼</td>
<td>▼</td>
<td>▲</td>
<td>Bag, saline lavage and suction. ? bronchoscopy</td>
</tr>
<tr>
<td>ETT occlusion</td>
<td>▼</td>
<td>▼</td>
<td>▲</td>
<td>Bag, saline lavage and suction. Reintubation</td>
</tr>
<tr>
<td>Alveolar recruitment</td>
<td>▲</td>
<td>▼</td>
<td>▲</td>
<td>Monitor for overdistension</td>
</tr>
</tbody>
</table>

∆P<sub>proximal</sub> is measured in the oscillator circuit and displayed on the ventilator.

Analgesia / sedation / Neuromuscular blocking agents

- Titrate analgesia and sedation to ensure tolerance (ie. < 5 cmH2O swing in mPaw) of HFOV.
- Use bolus doses of neuromuscular blocker agent (NMBA) in preference to continuous infusion.
- If continuous NMBA infusion required then adjust to lowest dose required to achieve tolerance of HFOV.

Infection Control (8)

The HFOV does not have exhaled gas filtering – therefore; routinely use expiratory gas scavenging.

Use Personal Protective Equipment (PPE) routinely - plus;
- If patient has known requirement for respiratory isolation or infectious state is unknown nurse in single room.
- Staff to wear PPE and use N95 masks.

Returning to Conventional ventilation (6,7)

Consider trial of CV when FiO2 < 0.4 and mPaw < 24 cmH2O

- Set up conventional ventilator / turn on.
- Set HFOV to standby.
- Clamp ETT and disconnect HFOV circuit.
- Attach conventional ventilator circuit using the following settings;
  - Assist / control
  - FiO2  0.1 > than HFOV setting
  - PEEP  15 cmH2O (? 5 cmH2O less than final mPaw)
  - PCV pressure  17 cmH2O(to achieve tidal volume of approx 6 mL/Kg)
  - Rate  15 breath per min
  - Ti  1.8 secs

ABGs in 15 mins – reassess settings.

Additional points

- Ensure humidifier chamber does not empty.
- In-line suction.
- Ensure HFOV circuit does not kink.
References


### Intensive Care, Prince of Wales Hospital
### HFOV – Bedside Guide

#### Goals of therapy

**Ventilation:** To maintain arterial pH in the range 7.20 to 7.35.

Consider administration of NaHCO₃ to accelerate metabolic compensation for respiratory acidosis if pH < 7.2. This will be the case if the PaCO₂ > 70 mmHg when the SBE is in the normal range.

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</tr>
<tr>
<td>Frequency = 6 Hz</td>
<td>FiO₂ = 1.0</td>
</tr>
<tr>
<td>If PaCO₂ &gt; 60 mmHg on conventional ventilation use;</td>
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</tr>
<tr>
<td>ΔP = 70 cmH₂O</td>
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<tr>
<td>Frequency = 5 Hz</td>
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</tbody>
</table>

#### Adjustments;

**pH in target range** –
(a) increase frequency by 1 to 2 Hz to max of 12 Hz

**pH is too high** – (correct metabolic alkalosis if indicated).
(a) increase frequency by 1 to 2 Hz to max of 12 Hz
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consider altered disease process:- possibility of pneumothorax, partial ETT obstruction, bronchospasm, de-recruitment).

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Allow 30 minutes between changes – use ABGs to guide.

**Failure of HFOV**

Increased PaCO₂ with pH < 7.2 despite maximum ΔP, frequency of 3 Hz, and cuff leak. (ensure ETT patency).

**Consider inhaled nitric oxide and/or prone position.**

Return to conventional ventilation.

#### Adjustments;

**If oxygenation below target** – increase mPaw by 5 cmH₂O steps (max of 45 cmH₂O) – consider recruitment manoeuvre (RM).

**If oxygenation is improving:**
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Allow 30 mins between steps for worsening oxygenation.

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Use SpO₂ and ABGs to guide.

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- Bronchoscopy
- Circuit disconnection
Recruitment manoeuvres

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Reset cuff leak
Restart piston

Recruitment manoeuvres algorithm at commencement of HFOV

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<th>Step 2</th>
</tr>
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<td>Measure ABGs 10 mins after RM  &lt;br&gt;Adjust ∆P and frequency  &lt;br&gt;Wean FiO2 in 0.1 steps every 2 minutes.  &lt;br&gt;Stop when: FiO2 = 0.4 or SpO2 = 88 – 95%</td>
</tr>
<tr>
<td>FiO2 &gt; 0.6 ?  &lt;br&gt;Repeat RM up to max of 3 cycles  &lt;br&gt;Consider further RMs 2 to 3 X per 24 hrs if FiO2 &gt; 0.4</td>
<td>FiO2 &lt; 0.6 ?  &lt;br&gt;Wean mPaw</td>
</tr>
</tbody>
</table>

Setting cuff leak

Reduce cuff pressure until mPaw falls by 5 cmH2O. Increase bias flow to re-establish original mPaw.

Consider size 6 ETT tube placed in hypopharynx if upper airway oedema (swelling, burns) to help gas escape.
**POW ICU**

**HFOV Data Collection**

**HFOV Criteria**

<table>
<thead>
<tr>
<th>Hospital No</th>
<th>Age</th>
<th>Gender</th>
<th>APACHE II</th>
<th>SAPS</th>
<th>LIS</th>
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Number of days on MV prior top HFOV

<table>
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<th>Diagnosis</th>
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<tr>
<th>At 0900 Pre HFOV</th>
<th>Start HFOV</th>
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</tbody>
</table>

**Outcome**

Duration of HFOV
Total days on MV
Failure of O2
Failure of CO2
Complications
Reason for withdrawal of HFOV
ICU survival
Hospital survival
Cause of death
Other therapy – NO or prone.
Definitions

Oxygenation Index = mean Paw X FiO₂ X 100/PaO₂

Lung Injury Score

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Finding</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>CXR</td>
<td>no alveolar consolidation</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>alveolar consolidation confined to 1 quadrant</td>
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</tr>
<tr>
<td></td>
<td>alveolar consolidation confined to 2 quadrants</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>alveolar consolidation confined to 3 quadrants</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>alveolar consolidation confined to 4 quadrants</td>
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<tr>
<td>Hypoxemia score</td>
<td>PaO₂/FiO₂ &gt; 300</td>
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<tr>
<td></td>
<td>PaO₂/FiO₂ 225 - 299</td>
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<td></td>
<td>PaO₂/FiO₂ 175 – 224</td>
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<td>PaO₂/FiO₂ &lt; 100</td>
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<tr>
<td>PEEP score</td>
<td>PEEP ≤ 5 cm H₂O</td>
<td>0</td>
</tr>
<tr>
<td>(if ventilated)</td>
<td>PEEP 6 - 8 cm H₂O</td>
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<td>PEEP 9 – 11 cm H₂O</td>
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<td>PEEP 12 - 14 cm H₂O</td>
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<td>PEEP &gt; 15 cm H₂O</td>
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<tr>
<td>Resp system</td>
<td>Compliance &gt; 80 mL/cm H₂O</td>
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<td>compliance score</td>
<td>Compliance 60 – 79 mL/cm H₂O</td>
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<td>Compliance 59 – 40 mL/cm H₂O</td>
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<td>Compliance 20 – 39 mL/cm H₂O</td>
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<td>Compliance ≤ 19 mL/cm H₂O</td>
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Score = (sum of parameter values) / number of parameters used.

Interpretation:
Score 0          no lung injury
Score 0.1– 2.5   mild to moderate lung injury
Score > 2.5      severe lung injury (ARDS)
SOFA Score

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<tr>
<th>Organ Score</th>
<th>0</th>
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<th>4</th>
<th>Day 1</th>
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<tbody>
<tr>
<td>Respiration (P/F)</td>
<td>&gt; 400</td>
<td>301 - 400</td>
<td>201 - 300</td>
<td>101 – 200</td>
<td>≤ 100</td>
<td>With resp support</td>
<td>With resp support</td>
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<td>Coagulation (platelets)</td>
<td>&gt; 150</td>
<td>101 – 150</td>
<td>51 - 100</td>
<td>21 - 50</td>
<td>≤ 20</td>
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<td>Liver (bilirubin)</td>
<td>&lt; 20</td>
<td>20 - 32</td>
<td>33 - 101</td>
<td>102 - 204</td>
<td>&gt; 204</td>
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<tr>
<td>CV (Hypotension)</td>
<td>None</td>
<td>MAP &lt; 70</td>
<td>Dopamine &lt; 5</td>
<td>Dopamine &gt; 5</td>
<td>Dopamine &gt; 15</td>
<td>Adren &gt; 0.1</td>
<td>Norad &gt; 0.1</td>
<td>Any vasopressin</td>
<td>Any aramine</td>
<td>Any phenylephrine</td>
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<td>Renal Creat or UO</td>
<td>&lt;0.11</td>
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<td>0.171 – 0.299</td>
<td>0.3 – 0.44</td>
<td>&gt;5.0</td>
<td>uo &lt; 500 ml/day</td>
<td>&lt; 200 ml/day</td>
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