Closed Loop Control of Mechanical Ventilation: State of the Art

Rich Branson

Why closed loop control?
- Reduce practice variation
- Enhance safety
- Respond to changes in patient condition which cannot be accomplished given staffing ratios and severity of illness
- Facilitate ventilator discontinuation
- Escalate therapy when required
- Provide standard of care regardless of environment and caregiver skill

What is closed loop?
- Feedback control – automatic manipulation of an output variable based on the measurement of an input variable(s)
- All ventilators utilize closed loop control
- Pressure support is a simple example of closed loop control – flow is manipulated to maintain a pre-selected pressure

Current State of the Art
- Mandatory minute volume (MMV)
- Adaptive pressure control (PRVC, APV, Volume control +, AutoFlow, etc)
- Adaptive support ventilation (ASV)
- AutoMode
- Proportional Assist (PAV)
- Neuromally Adjusted Ventilatory Assist (NAVA)
- SmartCarePS
On the Horizon
• Closed loop FIO2
• Closed loop FIO2/PEEP
• Complete closed loop control (Intellivent)

Adaptive Support Ventilation
• Uses body weight and Otis' WOB formula for determining variables
• Clinician sets PEEP, FIO2, and Pmax
• Ventilator algorithm chooses initial settings and modifies settings on a breath to breath basis
• Level of support determines weaning

Target Minute Ventilation

Calculate Optimal Breath Pattern: Minimal WOB
ASV Performance in Different Patient Diseases

Prospective study: 7 months period
1,499 days of invasive ventilation
Number of patients: 86

ASV: 98%

ASV European Multicenter Study

86 patients (+1 drop-out for respiratory instability)
59 males, 27 females
Age (years): 63 (range 28-85)
Actual Body Weight (Kg): 78 Kg (range 44 - 179)
Ideal Body Weight (Kg): 66 Kg (range 43 - 85)

Respiratory Disease:
- Normal lungs: 30%
- Restricted: 34%
- Obstructed: 36%

Conventional ventilation:
- VCV 60%
- PCV 40%

Humidification:
- HH 76%
- HME 24%

Is ASV on Target?

Utilization of an Automatic Mode of Ventilation (ASV) in a Mixed ICU Population: Prospective Observational Study

VT range: 5.6-10.4

Respiratory Disease:
- Normal lungs: 30%
- Restricted: 34%
- Obstructed: 36%

Conventional ventilation:
- VCV 60%
- PCV 40%

Humidification:
- HH 76%
- HME 24%

<table>
<thead>
<tr>
<th>Normal lungs</th>
<th>Respiratory disease</th>
<th>Acute lung injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT (%)</td>
<td>Vt range (ml)</td>
<td>ASV percentage</td>
</tr>
<tr>
<td>100%</td>
<td>5.6-10.4</td>
<td></td>
</tr>
</tbody>
</table>

Respiratory Disease:
- Normal lungs: 30%
- Restricted: 34%
- Obstructed: 36%

Conventional ventilation:
- VCV 60%
- PCV 40%

Humidification:
- HH 76%
- HME 24%
SmartCare (NeoGanesh)

- Pressure support ventilation
- Input: frequency, Vt, PetCO2
- Zone of acceptable ventilation
- Output: Pressure
- Adjustments every 2-5 minutes
- 12<f<28 b/min, Vt – 300 mL, PetCO2 < 55 mmHg
- If PSV is stable – suggests a SBT

Zone of acceptable ventilation

SmartCare PS
Success can be the result of the comparator

•

Four sites had protocols

Automated Weaning

**TABLE 2. COMPARISON OF OUTCOME BETWEEN STUDY GROUPS**

<table>
<thead>
<tr>
<th>Outcome</th>
<th>CDM Group (n = 70)</th>
<th>Standard Weaning Group (n = 70)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to first evaluation*</td>
<td>2.60 (2.1-3.1)</td>
<td>4.00 (2.94-5.29)</td>
<td>0.02</td>
</tr>
<tr>
<td>Duration of mechanical ventilation until first evaluation*</td>
<td>8.00 (5.75-10.70)</td>
<td>9.00 (7.54-12.10)</td>
<td>0.05</td>
</tr>
<tr>
<td>Time to successful evaluation*</td>
<td>5.00 (3.7-6.29)</td>
<td>6.00 (5.25-7.93)</td>
<td>0.11</td>
</tr>
<tr>
<td>Mechanical ventilation duration (days)</td>
<td>12.00 (8.0-12.89)</td>
<td>15.00 (10.0-20.80)</td>
<td>0.02</td>
</tr>
<tr>
<td>Hospital stay (days)</td>
<td>30.00 (27.0-44.25)</td>
<td>30.00 (27.0-44.25)</td>
<td>0.22</td>
</tr>
</tbody>
</table>

**ISSUES**

• Multicenter trial (5 sites)
• Four sites had protocols
• Not all sites used spontaneous breathing trials
• Compliance with protocols was not determined
• Success can be the result of the comparator
**AUTOMATED WEANING**

- Improved matching of ventilator output to patient need
  - Reducing practice variation
  - Complimenting clinician knowledge
  - Early detection of weaning readiness

Bouadma L. ICM 2005;31:1446-1450

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**Background**

- Oxygen represents 20%-30% of the weight of supplies for transport.
- Liquid oxygen provides the greatest volume but has storage, position, and off gassing issues.
- Cylinders are heavy and carry an explosive risk.
- Reducing oxygen usage has potential advantages.

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**Automated Weaning**

<table>
<thead>
<tr>
<th>Modality</th>
<th>MMV</th>
<th>ASV</th>
<th>MMV SmartCare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principle</td>
<td>Rate or PS to meet MV</td>
<td>We based VT/VE</td>
<td>PS to maintain pt comfort – VT, ETCO2</td>
</tr>
<tr>
<td>Breath type</td>
<td>VC-CMV, PS</td>
<td>Dual control SIMV/PS</td>
<td>PS</td>
</tr>
<tr>
<td>Set Variable</td>
<td>f and MV</td>
<td>MV/Pmax</td>
<td>None</td>
</tr>
<tr>
<td>Adaptation</td>
<td>7.5-10.0 sec</td>
<td>Breath to Breath</td>
<td>2-3 mins</td>
</tr>
<tr>
<td>Mode</td>
<td>CMV, SIMV, PS</td>
<td>SIMV+PS</td>
<td>PS</td>
</tr>
<tr>
<td>Automated SBT</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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**Study Goals**

- Closed loop control of inspired oxygen concentration (FiO2) using arterial oxygen saturation (SpO2) can
  - Reduce oxygen usage during transport.
  - Reduce the number of low SpO2 conditions.
  - Provide normoxemia vs. hyperoxemia.
Clinical Implications

- Reduced oxygen usage will reduce the weight and cube of required oxygen stores.
- Prevention of hypoxemia will improve outcome (a single episode of hypoxemia in closed head injury is associated with negative outcomes.)
- Closed loop can provide appropriate oxygenation for the patient from injury to definitive care.

Description

- $\text{FiO}_2$ automatically adjusted based on $\text{SpO}_2$, $\text{SpO}_2$-target difference and trends in $\text{SpO}_2$.
- $\text{SpO}_2$ target is 94% (adjustable).
- If $\text{SpO}_2 \leq 88\%$, $\text{FiO}_2$ increases to 1.0.
- A combination of fine and coarse control.
- If $\text{SpO}_2$ signal is lost, $\text{FiO}_2$ remains constant.
- If $\text{FiO}_2$ increases > 10%, an alert is provided.

Safety & Efficacy

- Safety – Prevention of hypoxemia ($\text{SaO}_2 \leq 88\%$)
- Efficacy – Ability of controller to maintain $\text{SaO}_2$ target (94% ± 2%)
- Oxygen conservation

Closed Loop $\text{FiO}_2$/SpO$_2$

- Total enrollment $n = 95$
- Gender 84 men, 16 women
- Ethnicity 73 Caucasian, 21 African-American, 1 Asian
- Mean age - 35.3 ± 11.7
- Mean Glasgow Coma Score – 10.8 ± 3.9
- Mean Injury Severity Score – 34 ± 13
- Mean APACHE II – 20 ± 7
Duration of Desaturation per Patient

Hypoxemia

Closed Loop FiO2/SpO2

Closed Loop FiO2/SpO2

* p < 0.0001

Oxygen conservation
Closed loop 0.02-5.9 L/min
Manual 0.9-7.7 L/min
**FiO₂ Changes**

- Closed loop 95.2 changes per 4-h period
- Control 4.4 changes per 4-h period
- 95 ± 49 vs. 4.46 ± 2 (p < 0.0001)
Closed Loop FIO2 in Neonates

- Hypoxemia and hyperoxemia have known severe consequences in the newborn
- Ideal environment for closed loop control
- NICU staff cannot keep up with the number of changes required to maintain normoxemia
- Current investigations of a PID controller designed by Claure known as CLiO
Closed Loop FIO2 in Neonates

Table 1. Frequency and duration of episodes of hypoxemia and bradycardia

<table>
<thead>
<tr>
<th>Type of Episode</th>
<th>Routine</th>
<th>Automated</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SpO2 &lt; 88%, ≤ 10 s</td>
<td>15 ± 5</td>
<td>23 ± 5</td>
<td>.001</td>
</tr>
<tr>
<td>Episode/hour</td>
<td>59 ± 16</td>
<td>52 ± 12</td>
<td>.136</td>
</tr>
<tr>
<td>SpO2 &lt; 75%, ≤ 19 seconds</td>
<td>6.1 ± 3.5</td>
<td>4.8 ± 3.7</td>
<td>.79</td>
</tr>
<tr>
<td>Episode duration (seconds)</td>
<td>32 (3-16)</td>
<td>24 (8-27)</td>
<td>.013</td>
</tr>
<tr>
<td>SpO2 &lt; 85%, ≤ 100 s</td>
<td>5.0 ± 3.8</td>
<td>2.5 ± 3.0</td>
<td>.002</td>
</tr>
<tr>
<td>(of episodes per 4 hours)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SpO2 &lt; 75%, ≤ 40 s</td>
<td>3.9 ± 3.3</td>
<td>2.6 ± 2.8</td>
<td>.002</td>
</tr>
<tr>
<td>(of episodes per 4 hours)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart rate &lt; 100 beats/min, ≤ 10 s</td>
<td>2.0 (0-3.3)</td>
<td>1.0 (0-2.0)</td>
<td>.01</td>
</tr>
</tbody>
</table>

Future

- Continued development
- Regulatory pathway? 510k or PMA?
- Thermostat for oxygen
- Regulatory burden may never be recovered
- How much would you be willing to pay for that?
IntelliVent®: Sensors/Signals

- Plethysmogram inspection
- Sensor reliability - QI derived
- "SpO2" = 15 last QI-weighted values
- 2 sensors possible
- No "SpO2" = controller freeze + alarm

IntelliVent®: Oxygenation controller

OXYGENATION GOAL: PaO₂ 55-80 mmHg or SpO₂ 88-95%

IntelliVent user set PEEP limit so don’t automatically ramp up to ARDSnet PEEP ranges
Lower/PEEP higher FIO2 used when increasing PEEP/FIO2
Higher PEEP table used when decreasing therapy (PEEP/FIO2)
FIO2’s higher than table will start to wean q30 minutes if SpO2 in range

IntelliVent: PEEP / FIO2 combinations

http://www.ardsnet.org/
IntelliVent Oxygenation controller: PEEP/FIO2

IntelliVent Oxygenation controller: PEEP/FIO2 rate of change

PEEP/FIO2 rate of change

<table>
<thead>
<tr>
<th>Action</th>
<th>Action definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease FIO2 stepwise</td>
<td>Decrease FIO2 by 5% of current FIO2 every 60s, minimal step size 1%</td>
</tr>
<tr>
<td>Increase FIO2 stepwise</td>
<td>Increase FIO2 by 10% of current FIO2 every 30s, minimal step size 1%</td>
</tr>
<tr>
<td>Decrease PEEP stepwise</td>
<td>Decrease PEEP every 360s (if quickly, 30s) by 2 cmH2O</td>
</tr>
<tr>
<td>Increase PEEP stepwise</td>
<td>Increase PEEP every 360s, Recruitment maneuver if last maneuver has been &gt;= 6 min ago and PEEP step is := 2 cmH2O</td>
</tr>
</tbody>
</table>

Note- if PEEP and FIO2 are changing, then FIO2 changes with PEEP, e.g. q 6 minutes
Conventional versus IntelliVent in post cardiac surgery

Prospective cross over controlled trial in Med-ICU

Conventional versus IntelliVent in post cardiac surgery

Pulmonary conditions

19 normal lungs patients:
12 coma, stroke, head trauma, meningitis...
7 septic shock

31 ALI/ARDS patients:
20 pulmonary injury: CAP, aspiration, chest trauma, post surgery pneumonia
11 extrapulmonary injury: septic shock, pancreatitis
## Ventilation

<table>
<thead>
<tr>
<th>All patients (n=50)</th>
<th>ASD</th>
<th>Intub/vent</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cases (nL/min/kg)</td>
<td>49 ± 12</td>
<td>37 ± 12</td>
<td>0.191</td>
</tr>
<tr>
<td>Leak (cmH2O/L)</td>
<td>17 ± 4</td>
<td>17 ± 4</td>
<td>0.970</td>
</tr>
<tr>
<td>RCcap</td>
<td>0.7 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>0.543</td>
</tr>
<tr>
<td>%TVi (%)</td>
<td>142 ± 27</td>
<td>114 ± 29</td>
<td>0.003</td>
</tr>
<tr>
<td>( V_{E/VTi} ) (LC/L/kg)</td>
<td>0.6 ± 0.6</td>
<td>0.1 ± 0.6</td>
<td>0.007</td>
</tr>
<tr>
<td>IB (breath/min)</td>
<td>15 ± 3</td>
<td>14 ± 3</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Peak (cmH2O)</td>
<td>29 ± 9</td>
<td>26 ± 8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Plate (cmH2O/L)</td>
<td>24 ± 6</td>
<td>22 ± 6</td>
<td>0.010</td>
</tr>
<tr>
<td>PEEP (cmH2O)</td>
<td>10 ± 4</td>
<td>9 ± 3</td>
<td>0.015</td>
</tr>
<tr>
<td>oxy (%)</td>
<td>45 ± 16</td>
<td>37 ± 13</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>pH</td>
<td>7.36 ± 0.08</td>
<td>7.28 ± 0.10</td>
<td>0.078</td>
</tr>
<tr>
<td>PaO2 (mmHg)</td>
<td>102 ± 26</td>
<td>91 ± 27</td>
<td>0.004</td>
</tr>
<tr>
<td>PaCO2 (mmHg)</td>
<td>35 ± 7</td>
<td>36 ± 7</td>
<td>0.984</td>
</tr>
<tr>
<td>SaO2 (%)</td>
<td>96 ± 3</td>
<td>86 ± 4</td>
<td>0.018</td>
</tr>
</tbody>
</table>

\[\text{Annu J Anes \& Intens Crit Care Med} \, \text{18} (2010):A004\]