Closed Loop Control of Mechanical Ventilation

Richard Branson MSc RRT
Professor of Surgery
Disclosures

**Honoraria or Research Support**

- Advanced Circulatory Systems Inc
- Bayer
- Medtronic
- Mallinckrodt
- Ventec LifeSystems Inc.
Closed Loop Systems

- **MMV** – mandatory minute ventilation
- **ASV** – adaptive support ventilation
- **SmartCare PS**
- **PRVC** - Pressure regulated volume control
- **PAV** – proportional assist
- **NAVA** – neurally adjusted ventilatory assist
- **Intellivent** – ASV + PEEP/FIO2 control
- **Closed Loop FIO2**
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
Improved Outcomes

- Shorter duration of weaning
- Reduced duration of mechanical ventilation
- Reduced complications
- Reduced costs
- Reduced clinician intervention
- Reduced sedation
- Reduced asynchrony
Adaptive Support Ventilation

- Uses body weight and Otis’ WOB formula for determining variables
- Clinician sets PEEP, FIO$_2$, and Pmax
- Ventilator algorithm chooses initial settings and modifies settings on a breath to breath basis
- Level of support determines weaning
Automatic selection of breathing pattern using adaptive support ventilation

Median Tidal Volumes/PBW

Jean-Michel Arnal
Marc Wysocki
Cyril Nafati
Stéphane Donati
Isabelle Granier
Gaëlle Corno
Jacques Durand-Gasselin

ICM 2008;34;75-81
### ASV for Weaning – Cardiac Surgery

<table>
<thead>
<tr>
<th>Results: MV Duration (HOURS)</th>
<th>Controlled</th>
<th>ASV</th>
<th>% change with ASV</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sultzer 2001</td>
<td>4.0</td>
<td>3.2</td>
<td>-20</td>
<td>p &lt; 0.02</td>
</tr>
<tr>
<td>Petter 2003</td>
<td>3.2</td>
<td>2.7</td>
<td>-15</td>
<td>NS</td>
</tr>
<tr>
<td>Gruber 2008</td>
<td>8.0</td>
<td>2.7</td>
<td>-66</td>
<td>p &lt; 0.05</td>
</tr>
<tr>
<td>Dongelmans 2009</td>
<td>16.3</td>
<td>16.2</td>
<td>-0.6</td>
<td>NS</td>
</tr>
<tr>
<td>Zhu 2015</td>
<td>7.0</td>
<td>3.6</td>
<td>-51</td>
<td>p &lt; 0.018</td>
</tr>
<tr>
<td>MEAN</td>
<td>12</td>
<td>5.7</td>
<td>-47</td>
<td></td>
</tr>
</tbody>
</table>

Duration of ventilation (hours) reduced by 25%
ASV for Support of ARF

- **Eighty-eight patients three groups:**
  - No obvious lung disease ($n = 22$),
  - Restrictive lung disease ($n = 36$)
  - Obstructive lung disease ($n = 30$).
- **Appropriate selection of $V_T$ and $Ti/Ttot$ based on mechanics**
- **In 3 COPD patients large tidal volumes were delivered (>12 mL/kg)**

Iotti G. Intensive Care Med
ASV for Support of ARF

ASV for Support of ARF

**ASV for Weaning**

- ASV vs. PS wean 97 COPD patients over 20 months
- ASV vs. PSV weaning
- ASV reduced wean to trach collar/extubation time from 3 days control group to 1 day in ASV group
- ASV provided shorter weaning times (median 24 (interquartile range 20–62) h versus 72 (24–144) h, \( p = 0.041 \)) with similar weaning success (35 out of 49 for ASV and 33 out of 48 for PSV).
- No difference in ICU LOS

Kirakali C. Eur Respir J 2011;38:774-780
Kirakali C. Eur Respir J 2011;38:774-780
Intellivent

Claviers Anesthesiol 2013:119’631.
Feasibility study on full closed-loop control ventilation (IntelliVent-ASV™) in ICU patients with acute respiratory failure: a prospective observational comparative study

Jean-Michel Arnal12*, Aude Garnero1, Dominik Novonti2, Didier Demory1, Laurent Ducros1, Audrey Berric1, Stéphane Yannis Donati1, Gaëlle Corno1, Samir Jaber3 and Jacques Durand-Gasselin1
Figure 2 Tidal volume selected by IntelliVent-ASV™: Tidal volume on predicted body weight ratio for normal lung patients, ARDS and COPD patients. For each lung condition, all patients, passive patients and active patients are shown on the left, middle and right box plot, respectively. Comparisons used a Kruskal-Wallis analysis of variance with a Dunn’s post hoc test. *P < 0.05. ARDS, acute respiratory distress syndrome; COPD, chronic obstructive pulmonary disease.
**Figure 3** $FIO_2$ selected by IntellVent-ASV™: $FIO_2$ for normal lung patients, ARDS and COPD patients. For each lung condition, all patients, passive patients and active patients are shown on the left, middle and right box plot, respectively. Comparisons used a Kruskal-Wallis analysis of variance with a Dunn’s post hoc test. *$P \leq 0.05$. ARDS, acute respiratory distress syndrome; COPD, chronic obstructive pulmonary disease; $FIO_2$, inspiratory fraction of oxygen (%).
• Cross over trial of PSV and Intellivent
• Twenty four hours in each period of observation
• n=7

Claviera Anesthesiol 2013:119’63
Clavieras Anesthesiol 2013:119’631.
Claviers Anesthesiol 2013:119’631.
Safety and efficacy of a fully closed-loop control ventilation (IntelliVent-ASV®) in sedated ICU patients with acute respiratory failure: a prospective randomized crossover study
Closed-loop ventilation mode (IntelliVent®-ASV) in intensive care unit: a randomized trial

Emilie BIALAIS 1,2 *, Xavier WITTEBOLE 1, Laurence VIGNAUX 3, Jean ROESELER 1, Marc WYSOCKI 5, Johannes MEYER 4, Gregory REYCHLER 2, Dominik NOVOTNI 4, Thierry SOTTIAUX 1,6, Pierre-François LATERRE 1, Philippe HANTSON 1

Table I.—Ranges of optimal and non-optimal zone of ventilation according to clinical condition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lung condition</th>
<th>Non-optimal</th>
<th>Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{V}_T$ (mL/kg IBW)</td>
<td>Normal lung/ARDS</td>
<td>&lt;3; &gt;12</td>
<td>6-10</td>
</tr>
<tr>
<td></td>
<td>Brain injury</td>
<td>&lt;3; &gt;12</td>
<td>6-10</td>
</tr>
<tr>
<td></td>
<td>Chronic hypercapnia</td>
<td>&lt;3; &gt;12</td>
<td>7-10</td>
</tr>
<tr>
<td>RR (breath/min)</td>
<td>Normal lung/ARDS</td>
<td>&lt;10; &gt;30</td>
<td>12-30</td>
</tr>
<tr>
<td></td>
<td>Brain injury</td>
<td>&lt;10; &gt;35</td>
<td>15-35</td>
</tr>
<tr>
<td></td>
<td>Chronic hypercapnia</td>
<td>&lt;10; &gt;35</td>
<td>15-35</td>
</tr>
<tr>
<td>$\text{P}_{\text{MAX}}$ (cmH$_2$O)</td>
<td>Normal lung/ARDS</td>
<td>&gt;30</td>
<td>6-25</td>
</tr>
<tr>
<td></td>
<td>Brain injury</td>
<td>&gt;30</td>
<td>6-25</td>
</tr>
<tr>
<td></td>
<td>Chronic hypercapnia</td>
<td>&gt;30</td>
<td>6-25</td>
</tr>
<tr>
<td>$\text{SpO}_2$ (%)</td>
<td>Normal lung/ARDS</td>
<td>&lt;90</td>
<td>92-96</td>
</tr>
<tr>
<td></td>
<td>Brain injury</td>
<td>&lt;90</td>
<td>Or if &gt;96 with PEEP&lt;8 cmH$_2$O and FiO$_2$&lt;40%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Or if &gt;96 with PEEP&lt;8 cmH$_2$O and FiO$_2$&lt;40%</td>
</tr>
<tr>
<td>$P_{\text{ET}}CO_2$ (mmHg)</td>
<td>Chronic hypercapnia</td>
<td>&lt;83</td>
<td>88-94</td>
</tr>
<tr>
<td></td>
<td>Normal lung/ARDS</td>
<td>&gt;55</td>
<td>25-45</td>
</tr>
<tr>
<td></td>
<td>Brain injury</td>
<td>&lt;26; &gt;43</td>
<td>30-33</td>
</tr>
<tr>
<td></td>
<td>Chronic hypercapnia</td>
<td>&lt;30; &gt;65</td>
<td>40-50</td>
</tr>
</tbody>
</table>

* tidal volume; RR: respiratory rate; $\text{P}_{\text{MAX}}$: maximum pressure; $\text{SpO}_2$: oxygen saturation measured by pulse oximetry; $P_{\text{ET}}CO_2$: end-tidal partial pressure of carbon dioxide; ARDS: acute respiratory distress syndrome.
<table>
<thead>
<tr>
<th>Percentage of time spent</th>
<th>IntelliVent-ASV®</th>
<th>Conventional ventilation</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-optimal ranges</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_T$ (%)</td>
<td>1.3 (2.0) [0.1-8.0]</td>
<td>0.8 (1.5) [1.1-4.3]</td>
<td>0.326</td>
</tr>
<tr>
<td>RR (%)</td>
<td>0.9 (3.1) [1.4-8.5]</td>
<td>1.7 (5.6) [2.7-14.1]</td>
<td>0.157</td>
</tr>
<tr>
<td>$P_{MAX}$ (%)</td>
<td>6.4 (41.3) [13.3-31.6]</td>
<td>0.0 (11.9) [7.1-30.4]</td>
<td>0.001*</td>
</tr>
<tr>
<td>$SpO_2$ (%)</td>
<td>0.5 (1.7) [0.6-3.0]</td>
<td>0.7 (3.1) [1.4-6.1]</td>
<td>0.097</td>
</tr>
<tr>
<td>$P_{ETCO_2}$ (%)</td>
<td>0.0 (0.4) [0.1-2.3]</td>
<td>0.1 (4.4) [1.6-15.8]</td>
<td>0.439</td>
</tr>
<tr>
<td><strong>Optimal ranges</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_T$ (%)</td>
<td>90.9 (14.2) [78.4-90.6]</td>
<td>81.9 (53.5) [60.1-79.7]</td>
<td>0.016*</td>
</tr>
<tr>
<td>RR (%)</td>
<td>87.3 (36.1) [68.3-84.3]</td>
<td>83.4 (33.2) [67.6-83.2]</td>
<td>0.729</td>
</tr>
<tr>
<td>$P_{MAX}$ (%)</td>
<td>54.9 (84.5) [41.6-65.6]</td>
<td>96.4 (88.6) [52.0-80.1]</td>
<td>0.042*</td>
</tr>
<tr>
<td>$SpO_2$ (%)</td>
<td>90.5 (20.3) [78.2-90.1]</td>
<td>67.0 (46.0) [61.9-77.9]</td>
<td>0.005*</td>
</tr>
<tr>
<td>$P_{ETCO_2}$ (%)</td>
<td>93.5 (39.2) [67.6-86.9]</td>
<td>89.7 (63.1) [56.1-80.8]</td>
<td>0.335</td>
</tr>
</tbody>
</table>
**Table VI.—Outcomes.**

<table>
<thead>
<tr>
<th></th>
<th>IntelliVent-ASV®</th>
<th>Conventional ventilation</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of invasive ventilation (days)</td>
<td>5.5 (11.0) [6.0-13.0]</td>
<td>8.0 (10.0) [6.5-15.3]</td>
<td>0.548</td>
</tr>
<tr>
<td>Length of ICU-stay (days)</td>
<td>11.5 (16.0) [10.8-20.8]</td>
<td>13.0 (14.0) [11.6-24.3]</td>
<td>0.433</td>
</tr>
<tr>
<td>Length of hospital-stay (days)</td>
<td>38.0 (57.0) [34.5-75.3]</td>
<td>46.0 (58.0) [41.0-72.7]</td>
<td>0.348</td>
</tr>
<tr>
<td>Mortality ICU, N. (%)</td>
<td>9 (21%)</td>
<td>11 (29%)</td>
<td>0.438</td>
</tr>
<tr>
<td>Mortality hospital, N. (%)</td>
<td>1 (3%)</td>
<td>5 (18%)</td>
<td>0.047*</td>
</tr>
<tr>
<td>Total mortality, N. (%)</td>
<td>10 (24%)</td>
<td>16 (42%)</td>
<td>0.080</td>
</tr>
</tbody>
</table>

Values are expressed as median (interquartile range) and [95% confidence interval for the mean] or number (%). *P<0.05; ICU: intensive care unit.
Are fewer RT/ventilator interactions an advantage?

To who?

Does this result in a lack of vigilance?

Figure 3.—Number of adjustments on the ventilator throughout the 48-hour ventilation: A) number of manual adjustments; B) total number of adjustments (including automatic adaptations).
SmartCare PS (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
Closed Loop PSV

• Tolerates instability of 2-4 mins
• Status evaluated at 2 min intervals
• If ventilation is ‘inadequate’ for > 2 mins and PSV < 15 cm H\textsubscript{2}O PSV $\uparrow$ 2 cm H\textsubscript{2}O, if PSV > 15 cm H\textsubscript{2}O $\uparrow$ PSV 4 cm H\textsubscript{2}O
• If PSV = 9 cm H\textsubscript{2}O for 2 hrs (stability) a message alerts the user to attempt a SBT

Dojat AJRCCM 2000;161:1161
A Multicenter Randomized Trial of Computer-driven Protocolized Weaning from Mechanical Ventilation

François Lellouche, Jordi Mancebo, Philippe Jolliet, Jean Roeseler, Frédérique Schortgen, Michel Dojat, Belen Cabello, Lila Bouadma, Pablo Rodriguez, Salvatore Maggiore, Marc Reynaert, Stefan Mersmann, and Laurent Brochard

![Graph showing probability of remaining on mechanical ventilation over days of mechanical ventilation. The graph compares Usual Weaning and CDW (Computer-driven Protocolized Weaning) with a p-value of 0.015.]

Usual Weaning: 70, 23, 9, 2, 1, 1
CDW: 74, 13, 4, 1, 1, 1

Days of mechanical ventilation: 0, 20, 40, 60, 80, 100, 120, 140
Automated Weaning

TABLE 2. COMPARISON OF OUTCOME BETWEEN STUDY GROUPS

<table>
<thead>
<tr>
<th>Outcome</th>
<th>CDW Group (n = 74)</th>
<th>Usual Weaning Group (n = 70)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to first extubation*</td>
<td>2.00 (1.75–6.25)</td>
<td>4.00 (2.00–8.25)</td>
<td>0.02</td>
</tr>
<tr>
<td>Duration of mechanical ventilation until first extubation*</td>
<td>6.50 (3.00–12.25)</td>
<td>9.00 (5.75–16.00)</td>
<td>0.03</td>
</tr>
<tr>
<td>Time to successful extubation†</td>
<td>3.00 (2.00–8.00)</td>
<td>5.00 (2.00–12.00)</td>
<td>0.01</td>
</tr>
<tr>
<td>Total duration of mechanical ventilation†</td>
<td>7.50 (4.00–16.00)</td>
<td>12.00 (7.00–26.00)</td>
<td>0.003</td>
</tr>
<tr>
<td>Intensive care length of stay</td>
<td>12.00 (6.00–22.00)</td>
<td>15.50 (9.00–33.00)</td>
<td>0.02</td>
</tr>
<tr>
<td>Hospital length of stay</td>
<td>30.00 (17.00–54.75)</td>
<td>35.00 (21.00–60.25)</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

Lellouche F AJRCCM 2006;174:894-900
Automated Weaning

- 102 patients
- Median time to suitability for weaning SmartCare 20 h vs. Control 8 h
- Median time to extubation SmartCare 43 h vs. Control 40 hours
- The study groups showed comparable rates of reintubation, non-invasive ventilation post-extubation, tracheostomy, sedation, neuromuscular blockade and use of corticosteroids.
- No advantage compared to experienced critical care specialty nurses, using a 1:1 nurse-to-patient ratio.
Automated Weaning

Schadler Am J Respir Crit Care Med Vol 185, Iss. 6, pp 637–644
Smart Care™ versus respiratory physiotherapy–driven manual weaning for critically ill adult patients: a randomized controlled trial

Corinne Taniguchi¹, Elivane S. Victor¹, Talita Pieri¹, Renata Henn¹, Carolina Santana¹, Erica Giovanetti¹, Cilene Saghabi¹, Karina Timenetsky¹, Raquel Caserta Eid¹, Eliezer Silva¹, Gustavo F. J. Matos¹, Guilherme P. P. Schettino¹ and Carmen S. V. Barbas¹,²*
Evaluation after 24 hours of Invasive Mechanical Ventilation

- Inclusion criteria
- Informed Consent signed
- Passed Daily Assessment

Measurements: Pmax, Pemax, VT, fVT and FVC

Randomization (opaque envelopes) 70 patients

- Respiratory Physiotherapy weaning driven protocol 35 patients
- Smart Care™ (Dräger, Germany) automatic weaning 35 patients

Spontaneous Breathing Trials (SBT)

- Successful
- Unsuccessful

1. Primary outcome:
   - Weaning duration (from randomization to extubation)

2. Secondary outcomes:
   - Extubation failure (need to return to invasive mechanical ventilation within 48 hours after extubation)
   - Mechanical ventilation time (from intubation to extubation)
   - Physiological measurements: respiratory rate (f), level of pressure support (PSV), tidal volume (TV), PEEP, FiO2, SpO2, EtCO2 and P0.1 at the beginning of the weaning trial and before extubation

Fig. 1 (See legend on next page.)
Smart Care™ versus respiratory physiotherapy–driven manual weaning for critically ill adult patients: a randomized controlled trial

**Table 3** Reintubation rate, ventilator malfunction and clinical complications in the two weaning protocols

<table>
<thead>
<tr>
<th></th>
<th>Weaning mode</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Respiratory physiotherapy–driven weaning</td>
<td></td>
</tr>
<tr>
<td>Reintubation rate</td>
<td>n</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5.7%</td>
</tr>
<tr>
<td>Ventilator related malfunction</td>
<td>n</td>
<td>0.0%</td>
</tr>
<tr>
<td>Clinical complications not related to the ventilatory mode itself</td>
<td>2</td>
<td>5.7%</td>
</tr>
</tbody>
</table>

**Table 5** Mechanical ventilation time and weaning duration in the two weaning protocols

<table>
<thead>
<tr>
<th></th>
<th>Weaning mode</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Respiratory physiotherapy–driven weaning</td>
<td></td>
</tr>
<tr>
<td>Mechanical ventilation time (days), median (IQR)</td>
<td>3.5 (2.0–7.3)</td>
<td>4.1 (2.7–7.1)</td>
</tr>
<tr>
<td>Weaning duration (min), median (IQR)</td>
<td>60.0 (50.0–80.0)</td>
<td>110.0 (80.0–130)</td>
</tr>
</tbody>
</table>

Abbreviation: IQR interquartile range
Smart Care™ versus respiratory physiotherapy–driven manual weaning for critically ill adult patients: a randomized controlled trial

Table 4 Respiratory parameters at the weaning start and end

<table>
<thead>
<tr>
<th>Weaning mode</th>
<th>Start of weaning</th>
<th>End of weaning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Respiratory therapy–driven weaning</td>
<td>SmartCare™ weaning</td>
</tr>
<tr>
<td>VT (ml)</td>
<td>Median (IQR)</td>
<td>Median (IQR)</td>
</tr>
<tr>
<td>f (breaths/min)</td>
<td>20 (16–24)</td>
<td>20 (17–24)</td>
</tr>
<tr>
<td>PSV (cmH2O)</td>
<td>8 (7–10)</td>
<td>10 (8–12)</td>
</tr>
<tr>
<td>PEEP (cmH2O)</td>
<td>8 (8–10)</td>
<td>8 (8–10)</td>
</tr>
<tr>
<td>FIO2 (%)</td>
<td>0.30 (0.25–0.30)</td>
<td>0.30 (0.25–0.30)</td>
</tr>
<tr>
<td>SpO2 (%)</td>
<td>99 (98–100)</td>
<td>99 (98–100)</td>
</tr>
<tr>
<td>P0.1 (cmH2O)</td>
<td>2.5 (0.7–4.2)</td>
<td>1.3 (0.7–2.5)</td>
</tr>
<tr>
<td>EtCO2 Mean (SD)</td>
<td>35.7 (7.4)</td>
<td>33.6 (8.2)</td>
</tr>
</tbody>
</table>
Closed Loop $FIO_2$ 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 FIO$_2$ in Neonates

Automated Adjustment of Inspired Oxygen in Preterm Infants with Frequent Fluctuations in Oxygenation: A Pilot Clinical Trial

Nelson Claure, MSc, PhD, Carmen D’Ugard, RRT, and Eduardo Bancelari, MD

Objective To assess the efficacy of a system for automated fraction of inspired oxygen (FIO$_2$) adjustment in maintaining oxygen saturation (SpO$_2$) within an intended range in preterm infants with spontaneous fluctuations in SpO$_2$.

Study design Sixteen infants (gestational age, 24.9 ± 1.4 weeks; birth weight, 678 ± 144 g; age, 33 ± 15 days) with frequent hypoxemia episodes underwent two 4-hour periods of FIO$_2$ adjustment by clinical personnel (routine) and the automated system (automated).

Results Compared with the routine period, the percent time within intended SpO$_2$ range (88%-95%) increased during the automated period (58% ± 10% versus 42% ± 9%; P < .001), whereas the percent time with SpO$_2$ higher than the intended range and ≥98% were reduced (9% ± 10% versus 31% ± 8% [P < .001] and 3% ± 5% versus 16% ± 9% [P < .001], respectively). Percent time with SpO$_2$ < 88% increased during the automated period (33% ± 7% versus 27% ± 9%; P = .003) because of more frequent episodes, whereas the time with SpO$_2$ < 75% did not differ. The 4-hour median FIO$_2$ was lower during the automated period (29% ± 4% versus 34% ± 5%; P < .001).

Conclusion Automated FIO$_2$ adjustment improved maintenance of SpO$_2$ within the intended range and reduced hypoxemia and FIO$_2$. These findings should be examined in longer periods with standard clinical conditions and, eventually, in the context of randomized trials powered to detect clinically important effects on outcome. (J Pediatr 2009;155:640-5).
Closed Loop $FIO_2$ in Neonates

Table I. Time within or outside the intended $SpO_2$ range, and time in severe hypoxemia or hyperoxemia

<table>
<thead>
<tr>
<th>$SpO_2$ Level</th>
<th>Routine Mean (SD)</th>
<th>Automated Mean (SD)</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>88%-95%</td>
<td>42 ± 9</td>
<td>58 ± 10</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>&gt; 95%</td>
<td>31 ± 8</td>
<td>9 ± 10</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>≥ 98%</td>
<td>16 ± 9</td>
<td>3 ± 5</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>&lt; 88%</td>
<td>27 ± 9</td>
<td>33 ± 7</td>
<td>.003</td>
</tr>
<tr>
<td>&lt; 85%</td>
<td>22 ± 8</td>
<td>25 ± 7</td>
<td>.1</td>
</tr>
<tr>
<td>&lt; 75%</td>
<td>6.6 ± 5.6</td>
<td>4.6 ± 3.4</td>
<td>.114</td>
</tr>
<tr>
<td>&lt; 70%</td>
<td>2.5 (0.5-4.1)</td>
<td>1.1 (0.2-1.7)</td>
<td>.005</td>
</tr>
</tbody>
</table>

Data in mean ± SD or median (25th-75th percentile).
Closed Loop $FIO_2$ in Neonates

Table II. 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>$SpO_2 &lt; 88%$, $\geq 10$ s</td>
<td>$15 \pm 5$</td>
<td>$23 \pm 5$</td>
<td>.001</td>
</tr>
<tr>
<td>Episodes/hour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Episode duration (seconds)</td>
<td>$59 \pm 16$</td>
<td>$52 \pm 12$</td>
<td>.136</td>
</tr>
<tr>
<td>$SpO_2 &lt; 75%$, $\geq 10$ s</td>
<td>$5.1 \pm 3.5$</td>
<td>$4.8 \pm 3.7$</td>
<td>.79</td>
</tr>
<tr>
<td>Episodes/hour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Episode duration (seconds)</td>
<td>$32 (23-39)$</td>
<td>$24 (16-27)$</td>
<td>.013</td>
</tr>
<tr>
<td>$SpO_2 &lt; 85%$, $&gt;120$ s</td>
<td>$5.5 \pm 3.8$</td>
<td>$2.5 \pm 3.0$</td>
<td>.022</td>
</tr>
<tr>
<td>(# of episodes per 4 hours)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$SpO_2 &lt; 75%$, $&gt;60$ s</td>
<td>$3.9 \pm 3.3$</td>
<td>$2.0 \pm 2.8$</td>
<td>.022</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, $\geq 10$ s</td>
<td>$2.0 (0.3-3.8)$</td>
<td>$1.0 (0.0-2.0)$</td>
<td>.01</td>
</tr>
<tr>
<td>(# of episodes per 4 hours)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Episodes of hypoxemia with $SpO_2 < 75\%$ are a subset of those with $SpO_2 < 88\%$. Data in mean $\pm$ S.D. or median ($25^{th}$-$75^{th}$ percentile).
Closed Loop FIO$_2$ in Neonates
Closed Loop FIO₂ in Neonates
Closed Loop \( \text{FIO}_2 \) in Neonates
Closed Loop FIO2 in Adults

- 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.
Description

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

• **Total enrollment** $n = 95$
• **Gender** 79 men, 16 women
• **Ethnicity** 73 Caucasian, 21 African-American, 1 Asian
• **Mean age** - $35.3 \pm 11.7$
• **Mean Glasgow Coma Score** – $10.8 \pm 3.9$
• **Mean Injury Severity Score** – $34 \pm 13$
• **Mean APACHE II** – $20 \pm 7$
Duration of Desaturation per Patient

Total Duration of DSAT by Patient

Total Duration of DSAT (minutes)

1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70 73 76 79 82 85 88 91

- Close_loop
- Manual
Closed Loop FiO₂/SpO₂

Minutes at each level of oxygen saturation

* p < 0.0001
Hypoxemia

*p = 0.0017

Total Duration of DSAT of SPO2 <=88 (Minutes) of 95 Patients

Mean duration (minutes)

1.28

0.57

Treatment

Manual

Close_loop

*p = 0.0017
Closed Loop FiO₂/SpO₂

* p < 0.0001

Oxygen conservation

Closed loop 0.02-5.9 L/min

Manual 0.9-7.7 L/min
FiO$_2$ Changes

- Closed loop 95.2 changes per 4-h period
- Control 4.4 changes per 4-h period
- $95 \pm 49$ vs. $4.46 \pm 2$ ($p < 0.0001$)
CLC of FIO$_2$

- If excessive FIO$_2$ exposure is harmful – CLC of FIO$_2$ is the solution.
- Areas of concern
  - Greater risk of hypoxemic exposure
  - Lack of caregiver awareness
  - Lack of knowledge regarding the need for hyperoxia (CO poisoning, profound anemia)
Autonomous – CLC O2

- CLC-FiO2
- O2 needs based
  - SpO2

A key feature with autonomous therapy is that the activity of the feedback controller (closed loop control [CLC]) provides an index of injury severity.

CLC-FiO2 study – the CLC activation occurred hours before PE by CT scan.
The use of smart oxygenation systems (SOS) for diagnosing and treating lung injury will provide more rapid life-saving interventions (LSI’s) and better outcome.
CLC-FiO2 Controller

Pilot studies
Sheep: 40% TBSA Burn + Smoke injury model
Spontaneously breathing

CLC-FiO2 activity FiO₂ increase > 0.2
Occurs 2-3 hour before tachypnea
Rescue Ventilation [RV]

Data shows time rescue ventilation [LSI] initiated vs S/F ratio < 250

SOC – Rescue ventilation 4.7 ± 0.6 Hr
SOS – Rescue ventilation 0.3 ± 0.1 Hr [rapid onset b/w Dx & Rx]
Improved Outcomes?

• Shorter duration of MV – SmartCarePS and ASV (cardiac surgery)
• Reduced clinician intervention – all
• No evidence for reduced cost or complications
• Some concern about maintaining LPV
• Concerns of how to monitor
• Lack of vigilance?
• These modes perform as intended
Summary

• No large trials demonstrating superiority of automated ventilation using important outcome variables
• Reduces practice variation and may play an important role in resource limited environments
• Patient population and current standards of care are important comparators for research design
• Clinician acceptance remains an impediment to further use